A BASIN ANALYSIS OF THE TRANSVAAL SEQUENCE IN THE POTCHEFSTROOM SYNCLINORIUM, TRANSVAAL AND ORANGE FREE STATE

by

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ABSTRACT

A basin analysis involves an examination of the basin geometry, directional structures, lithic fill, arrangement of the lithic fill, and the tectonic setting of the basin (Potter and Pettijohn, 1963, p. 227). While it was not possible to define paleocurrent patterns, the remaining four of the above elements, as related to the lower units of the Transvaal Sequence, namely; the Malmani Dolomite, Fountains, and Timeball Hill Formations, within that area now occupied by the Potchefstroom Synclinorium, have been examined in detail.

The present geometry of the Potchefstroom Synclinorium has been outlined through the interpretation of outcrop patterns, and through the preparation of residual structure contour maps, after subjecting borehole depth data to trend surface analysis. Numerous longitudinal and transverse structural trends and associated domes and basins have been recognized, the more important of which are the Johannesburg and Vredefort Domes, the Potchefstroom and Marievale Anticlines, the Carletonville Syncline, and the Hartbeestfontein Anticline, while the Ottosdal Anticline and a basement high through Standerton and Senekal were also found to have influenced the development of the synclinorium. Isopach studies have revealed that the above structural trends, apart from the basement high to the south and possibly the Vredefort Dome, have experienced periods of activity and inactivity, related to pulsating tectonic movements within the basement, since pre-Witwatersrand Sequence times, and that the present geometry of the synclinorium is post-Transvaal Sequence in age.

The study of the lithology of the Malmani Dolomite was hampered by the poor outcrop of this formation. However, with the aid of a number of borehole cores, a stratigraphic column for this formation has been constructed, in which a cyclical depositional facies was recognized. Examination of the Fountains Formation was carried out mainly in the field, making it possible for a subdivision to be made into the brecciated chert zone, at the base, and the Pologround Member. Borehole data and measured field sections revealed that the Timeball Hill Formation varies in character within the synclinorium. Whereas along the northern limb carbonaceous and laminated ferruginous shales with thick, massive quartzites are present, the content of the former shale-type decreases southwards until, on the periphery of the Vredefort Dome, only the ferruginous variety occurs, in association with lenticular quartzites.

Individual zones within the Malmani Dolomite were found to be homogeneous over great distances. Insufficient data for the construction of facies maps was available, but a thickening of this formation to the northwest was recognized. Isopach maps for the Fountains Formation indicate that the brecciated chert zone attains maximum thicknesses over structural highs, and that the Pologround Member has a channel geometry. Isopach maps as well as facies maps were prepared for the Timeball Hill Formation. An overall decrease in quartzite percentage to the south is

apparent, suggestive of a northerly source. Isopach maps indicate that, whereas the Johannesburg Dome was active during Timeball Hill formation times, the area now occupied by the Vredefort Dome was tectonically negative.

The Malmani Dolomite and Pretoria Group are considered to be classic examples of contrasting styles of sedimentation. During the deposition of the former, a shallow-water environment on a highly stable craton prevailed. Chemical sedimentation was favoured, with only minor amounts of clastic material being introduced into the depository. Uplift at the end of Malmani Dolomite times resulted in subaerial weathering of this formation, with the development of the residual brecciated chert zone. Related to the uplift, which was most pronounced along the Hartbeestfontein Anticline, a major unconformity was developed at the top of the Malmani Dolomite. Above the brecciated chert zone, detrital sedimentation predominates, apart from occasional chert horizons and dolomitic shales towards the base. A boulder conglomerate at the base of the Pologround Member represents a response to sudden uplift, which was followed by the introduction of sand and clay from a cratonic source area to the north of the Potchefstroom Synclinorium, deposition of the latter sediments having taken place in a deltaic environment. A period of major uplift along the Hartbeestfontein Anticline marked the end of the Timeball Hill depositional period, with the development of a second major unconformity at the top of this formation.

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INTRODUCTION

Aims of Research

The hundreds of boreholes, drilled in search of the banket within the main Witwatersrand Basin, many of which penetrated overlying formations, presented an ideal opportunity for an investigation of the structure and stratigraphy of the Transvaal Sequence in the Potchefstroom Synclinorium. This project was undertaken with the following aims in mind :

i) To extend the lithostratigraphic subdivision of the Transvaal Sequence into the Potchefstroom Synclinorium.

ii) To determine the structural evolution of the Potchefstroom Synclinorium from Witwatersrand to Transvaal times.

iii) To construct a stratigraphic column for the Malmani Dolomite Formation of the Transvaal Sequence, and to investigate the change in thickness of this formation within the synclinorium.

iv) To investigate the stratigraphy of the Fountains and Timeball Hill Formations, and the arrangement of these formations within the Potchefstroom Synclinorium.

v) To outline the environment of deposition of the Transvaal Sequence, to the top of the Timeball Hill Formation, and to investigate the relationship of the occurrence of this sequence within the Potchefstroom Synclinorium to that in the main Transvaal basin.

Locality and Regional Geological Setting of the Area

The area under investigation has been termed the Potchefstroom Synclinorium, occurring in the southern parts of the Transvaal and extending across the Vaal River into the northern Orange Free State (Figure 1). Major towns are located throughout the area, including those of the Reef from Randfontein through Johannesburg to Springs. The large industrial centres of Vanderbijlpark and Vereeniging occur to the south-east, with Klerksdorp and Orkney serving the western limits of the area. Potchefstroom, centrally situated with respect to the previously mentioned centres, is the largest town within the synclinorium.

The present study is concerned exclusively with rock types of the Transvaal Sequence developed in the Potchefstroom Synclinorium, underlain for practically their whole extent by Ventersdorp Sequence volcanics and sediments (Figure 4). The northern limb of the structure is underlain by formations of the Witwatersrand Sequence and basement granites and

DISTRIBUTION OF THE TRANSVAAL SEQUENCE IN THE TRANSVAAL AND NORTHERN ORANGE FREE STATE

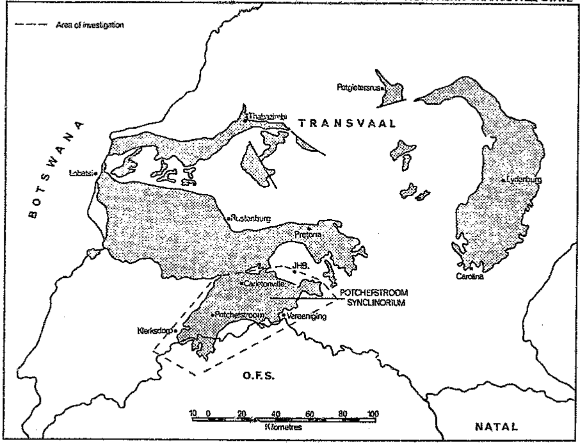

Figure 1.

gneisses, the former also underlying the Ventersdorp Sequence on outcrop around the major extent of the synclinorium. The outcrop of the Transvaal Sequence is that of a refolded syncline, following the older systems in a broad arcuate structure around the Vredefort Dome. Examination of the Transvaal Sequence was limited on the extremities of the synclinorium in the Kroonstad and Wolwehoek regions (Figure 2) by a cover of younger Karroo formations and lack of subsurface information.

Previous Work

The earliest comprehensive geological investigation of the Transvaal Sequence in Potchefstroom Synclinorium was that by Hatch (1903) who described two cross-sections north of Potchefstroom. Draper (1897) (according to Molengraaf, 1904) constructed an idealized section across the West Rand Anticline to the south-west of Krugersdorp. The same author also described the Malmani Dolomite Formation in some detail, dividing the formation into the Black Reef and Dolomite Series. The first detailed mapping in the area was undertaken by Mellor (1907), when he mapped most of the area north of the Vaal River occupied by beds of the Transvaal Sequence. This mapping was later extended further northwards to incorporate those portions of the Transvaal Sequence associated with the Central and West Rand Goldfields (Mellor, 1917). Truter (1936) resurveyed 95 square miles of this area in the immediate vicinity of Potchefstroom. Isolated outcrops of agglomerates and tuffs, similar to pre-Transvaal rock-types, were discovered in this area within the Malmani Dolomite Formation. This suggested a complex structural history for the area and led to the recognition of the Mooi River thrust fault for the first time. The work of Mellor (1907) and Truter (1936), combined with additional field-work, was used in the compilation of the geological map of the country around Potchefstroom and Klerksdorp by Nel and others (1939). The remaining north-western and south-eastern portions of the synclinorium were mapped and reported on by Nel and others (1935) and by Nel and Jansen (1957), respectively. Mapping of the area between Bothaville and Vredefort was undertaken by Nel and Verster (1962), incorporating those Transvaal Sequence rocks south of the 27th parallel. Detailed mapping of successions flanking the Vredefort Dome (Nel, 1927) revealed the structural disposition of the Transvaal strata in this region.

Recent work in the Potchefstroom Synclinorium has been based largely on subsurface data, with over 500 boreholes passing through the base and some 100 through the full succession of the Malmani Dolomite Formation. The boreholes were drilled by different mining companies, as part of exploration programmes outlining extensions to the Witwatersrand goldfields. Apart from two isolated localities, the boreholes were drilled on the north-west flank of the synclinorium and, in particular, in the West Rand, Far West Rand, and Klerksdorp areas. Detailed work on the West Rand and Far West Rand, using borehole data from the Transvaal Sequence, has been undertaken by Brock (1961), Cousins (1962) and, more recently, by De Kock (1964). Investigations on a more regional scale were made by Papenfus (1964) who prepared a structure contour map of the base of the Transvaal Sequence over the whole synclinorium, and by Brock and Pretorius (1964a) who briefly discussed sedimentation and tectonic patterns within the sequence, as related to "Rand Basin subsidence". Few detailed investigations have been carried out on the Malmani because of poor outcrop of this succession in the synclinorium. Young (1934) examined dolomite cores from the Carletonville area, recognizing different phases within the depositional history of the formation. Further observations, including the development of the formation in the Klerksdorp area, were made by Toens (1966) who attempted to correlate different horizons within the formation across the synclinorium.

Apart from gold recovered from the Black Reef Member, as outlined by Papenfus (1964), little other exploitation of the sequence has taken place. Three intrusive complexes occur within the sequence, but only that on Roodekraal 451 appears to be of any economic interest (Nel and others, 1939).

Nature of Research

During the initial stages of the present investigation, data on structure, thickness, and stratigraphy was collected from published and unpublished borehole logs. After having accumulated all available published information, the records of different mining companies were examined for additional and more detailed data. At this stage, over 500 control points, recording the depth to the base of the Black Reef, were available for analysis, as well as 100 Malmani Dolomite thickness values, and useful stratigraphic data for the Timeball Hill Formation at 25 localities.

A number of borehole cores, which include the complete Malmani Dolomite Formation, have been preserved by Anglo American Corporation of South Africa, Limited, and Johannesburg Consolidated Investment Company, Limited. These provided an ideal opportunity for an examination of this relatively unknown stratigraphic unit. Detailed stratigraphic columns were prepared from a number of cores, while samples were taken throughout the formation for chemical analysis. In an attempt to more accurately define the stratigraphy of this formation, field observations were made to the north of Krugersdorp, where good outcrops of the Malmani Dolomite occur. Stratigraphic information from borehole logs, for the Timeball Hill Formation, is confined largely to the north-western limb of the Potchefstroom Synclinorium. Numerous field sections for this formation were measured in the northern, eastern, and south-eastern portions of the synclinorium, to compliment the borehole data. At this stage, field checking of published information was also carried out.

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LITHOSTRATIGRAPHIC NOMENCLATURE

Problems of Stratigraphic Nomenclature

The acceptance of an international stratigraphic nomenclature has met with many problems since initially proposed at the first International Geological Congress in 1878. This subject has been reviewed in detail (Dunbar and Rogers, 1957; Verwoerd, 1964) who have outlined the stages in its development while Truswell (1967) noted the dissenting views of Russia and South Africa to the proposal.

Any stratigraphic terminology is based on the recognition of certain inherent properties of a lithologic succession, enabling a subdivision of, and lateral correlation within, the sequence to be made. The International Subcommission for Stratigraphic Terminology (1961) proposed a stratigraphic classification based on specific properties (Table 1) which was finally accepted in 1971 by the South African Committee for Stratigraphy, with the appointment of a number of working groups to revise the South African column according to the new code.

TABLE 1

Characters of Attributes of Rock Strata	Units	
	Informal	Formally Named
Lithology - Rock Character		Group
	Zone	Formation
	bed(s)	Member
(Lithostratigraphic Classification)		Bed(s)
Palaeontology - Fossil Content		Zone :
(Biostratigraphic Classification)	Zone	Assemblage - zone
		Range - zone
Geochronology - Geologic Age		Erathem
	Stage	System
		Series
(Chronostratigraphic Classification)	Chrono-zone	Stage
		Substage

In the correlation and subdivision of Precambrian strata, such as the Transvaal Sequence, fossils are either absent or poorly developed, and use must be made of lithology or geochronology. This, according to Newton

(1968), involves correlation as used in two senses. Firstly, it is necessary to indicate the identity between two physically separated occurrences of similar lithology, and, secondly, to indicate that two or more separate bodies of rock were laid down contemporaneously. On this basis, subdivision of a thick succession into a number of units would also be possible. The principles outlined above have been extensively followed in the past, on the assumption that lithologic boundaries can be equated with time boundaries. This is, however, seldom the case for sedimentary sequences, whether they be of chemical or detrital origin. Many such deposits form under transgressive/regressive conditions, independant of the slope of the basin floor, and are therefore diachronous in nature. Even though lithologic units may be "close enough to time so the difference doesn't matter", as discussed by Shaw (1964, p. 39), 'time' lines cannot be considered as being parallel to lithic boundaries. Chronostratigraphic subdivision of like lithologic rock types thus became unacceptable.

A reappraisal of stratigraphic nomenclature took place with the result that the lithostratigraphic classification (Table 1) is now almost universally accepted. This purely lithological terminology has been reviewed by Truswell (1967) who stated that lithostratigraphic terms show no equivalence whatsoever to chronostratigraphic units and that they can be applied to rocks of any age. According to lithostratigraphic nomenclature, formation becomes the basic unit, and is defined in terms of uniformity of lithology, alternations, or cycles of lithology, or even heterogeneity as long as this is distinctive (Newton, 1968). The same writer stresses that a formation should be an easily mappable unit. Any sequence can thus be divided into a number of formations on the basis of lithology, without regard to the time-span covered or the thickness of each formation. Individual formations are designated by geographic names derived from a locality or area of typical development of the unit, and, when dominated by a single rock type, formations are appropriately designated by the characterizing lithology (Code of Stratigraphic Nomenclature, 1961).

Newton (1968) also defined the lower-order terms of 'member' and 'bed'. A member is considered as a subdivision of formation, to be used if convenient or necessary, while it is not essential that the complete formation should be divided into members. The terms 'lentil' and 'tongue' are synonymous with 'member'. The term 'bed' which is the smallest unit of the hierarchy is only used in a formal sense where a bed of particular importance justifies this, in being distinctive and particularly useful to recognize. According to the Code of Stratigraphic Nomenclature (1961) a group is the rock-stratigraphic unit higher in rank than a formation, consisting of two or more formations which are related in some way, but it is not necessary to assemble all formations in a sequence into groups (Newton, 1968). The stratigraphic record of major continental areas is subdivided by major unconformities which can be traced in outcrop and in the subsurface. Krumbein and Sloss (1963, p. 35) have designated these unconformity-bounded stratiform assemblages as 'sequences' which is the highest-order term in the lithostratigraphic hierarchy.

Lithostratigraphic Nomenclature within the Transvaal Sequence

Before attempting to re-express the stratigraphy of the Transvaal Sequence in lithostratigraphic terms, the status of the Ventersdorp Sequence, as recognized at present, warrants a short review. Once this has been done, it can be appreciated that the base of the Transvaal Sequence is in all probability not at the base of the Black Reef, as is generally accepted, but rather somewhat lower in the stratigraphy.

Using sub-surface data in the Bothaville district, Winter (1965) was able to outline the tectonic framework of the Ventersdorp Sequence in that area. Based on these findings he concluded that the Ventersdorp Sequence "is not a unit", but that the lower Ventersdorp displays greater affinity with the Upper Witwatersrand Sequence, and the Upper Ventersdorp with the Transvaal Sequence, while the Middle Ventersdorp is a unit on its own. Winter (1965) then suggested that the Upper Ventersdorp could be considered as the lowermost subdivision of the Transvaal Sequence, termed the Pniel Series, as first described by Stow and Jones (1874) for a similar sequence of rock-ty in Griqualand West. These views are substantiated by the fact that volcanics persist into the basal members of the Transvaal Sequence in the Vryburg area (du Toit, 1954). In the light of the preceding discussion, the suggestion is now made that the upper parts of the Ventersdorp Sequence, as developed below the Black Reef, particularly along the southern and western margins of the synclinorium (Figure 4), may be included as a basal phase of the Transvaal Sequence in parts of the area investigated. In accordance with lithostratigraphic nomenclature, it is suggested that this phase be referred to as the Pniel Group, so defining a type area of development (du Toit, 1954, p. 116). The validity or confirmation of this subdivision and the accurate delineation of the base of the Pniel Group will, however, require detailed field and stratigraphic mapping. This will also reveal whether or not the Upper Ventersdorp Sequence is developed throughout the full extent of the synclinorium. Since no detailed work was carried out on the Black Reef - Ventersdorp relationship during the present investigation, the succeeding discussion will be confined to the rock-types above the volcanics, save to outline the pre-Black Reef geology (Figure 4).

The nomenclature of the Transvaal Sequence from the base of the Malmani Dolomite was first revised by Truswell (1966) on a regional scale, and later more locally by Button (1968) in the Irene - Delmas - Devon area. The proposed stratigraphic nomenclature of the Transvaal Sequence in the area under investigation is shown in Table 2 and is seen to differ somewhat from that proposed by Truswell (1966) and Button (1968). While appreciating the difficulties inherent in the system of lithostratigraphic nomenclature, the need for some uniformity of terms and formational bounding surfaces seems desirable, and it is hoped that in the near future a more lucid presentation of the Transvaal Sequence stratigraphy will be possible. The formational subdivision proposed in Table 2 conforms to the Code of Stratigraphic Nomenclature (1961) regarding the mappability and lithologic characteristics of the individual formations. The existence of well-defined unconformities has been used as an additional parameter in this subdivision.

TABLE 2

LITHOSTRATIGRAPHIC NOMENCLATURE OF THE TRANSVAAL SEQUENCE IN THE POTCHEFSTROOM SYNCLINORIUM

SEQUENCE	GROUP	FORMATION	MEMBER
TRANSVAAL	PRETORIA	Ongeluk	
		Timeball Hill	Gatsrand
		Fountains	Pologround
		Malmani Dolomite	
			Black Reef Quartzite
	PNIEL		
?		?	?

Malmani Dolomite

This formation is defined mainly on its lithologic characteristics, being composed almost exclusively of authochthonous sediments (Shaw, 1964, p. 14), with minor intercalated material of detrital origin. The name 'Malmani Dolomite' was re-introduced by Button (1968), after first having been used by Draper in 1894 (Haughton, 1938) to replace 'Dolomite Series', and has been retained as a definitive term. The basal clastic unit was given member status as it is not developed throughout the synclinorium, and therefore does not constitute a mappable unit as such. Although not strictly correct in that it does not define a type locality, the well-known name 'Black Reef' (Penning, 1891) was retained for this unit, in an attempt to keep the nomenclature as simple as possible. The base of the Malmani Dolomite Formation can be clearly delineated on lithologic grounds except on the northern flank of the synclinorium where this formation transgresses northwards onto the basement granite, in part overlying the Witwatersrand System where lithologic similarities between the latter and the Black Reef Member are encountered.

Fountains Formation

The Fountains Formation which, as mentioned above, unconformably overlies the Malmani Dolomite was first described by Button (1968) as typically developed at Fountains near Pretoria. In the Potchefstroom Synclinorium, this rock-stratigraphic unit consists of brecciated chert boulders in a gritty matrix, or gritty horizons which may contain minor interlayered shales. The chert boulder bed, where developed, and the gritty horizons are of limited areal extent and are termed the Pologround Member, while the formation as a whole constitutes a readily recognizable and therefore easily mappable unit in the field. There is no evidence of an unconformity between the Fountains and Timeball Hill Formations, leading to the former being considered as part of the Pretoria Group.

Timeball Hill Formation

Mollengraaf in 1897 (Haughton, 1938) originally described the quartzites of the Timeball range in Pretoria as the Timeball Hill Quartzite, suggesting that this name could possibly be used for the equivalent stratigraphic horizon in the Potchefstroom Synclinorium. The possibility of these quartzites, as developed in the synclinorium, being termed the Timeball Hill Formation was considered, but due to their impersistent and often lenticular nature, as will be discussed later, this was decided against. The name Timeball Hill Formation was adopted instead for the alternating succession of shales and quartzites with diabase intrusives immediately above the Fountains Formation. Part of the 'Lower Daspoort Series' was included in this formation which constitutes in itself a cycle of deposition. A local name, 'Gatsrand', was introduced for the quartzite horizons often containing intercalated shales which were given member status. The Gatsrand Member is most typically developed along a range of hills stretching west and south-west through the Potchefstroom district where Mollengraaf in 1891 (Haughton, 1938) first described the equivalent of the Pretoria Group as the 'Gatsrand Series'. The upper limit of the Timeball Hill Formation is defined by an unconformity of pre-Ongeluk Formation age. The base of the latter formation was not easily delineated in the field, but was taken to underlie, where developed, the Daspoort Tillite (Kynaston, 1929) or Lower Ongeluk Quartzite representing the basal phase of the Ongeluk Formation, or the Ongeluk Volcanics where the tillite and quartzite were absent. As the present investigation did not include a study of the volcanics, the stratigraphy of the Ongeluk Formation will not be discussed in succeeding chapters.

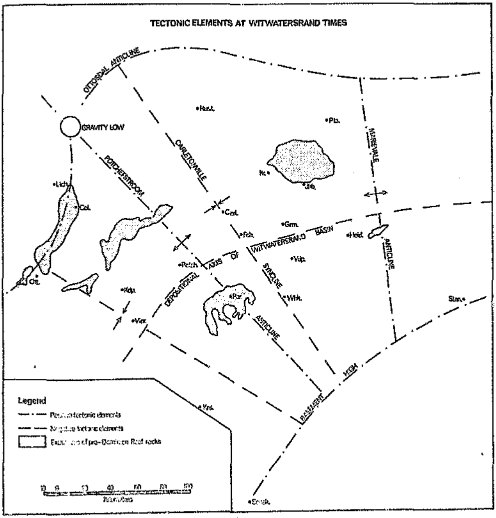

TECTONIC ELEMENTS AT WITWATERSRAND TIMES
OTTOSDAL ANTICLINE
GRAVITY LOW
POTCHEFSTROOM
CARLETONVILLE
MAREVALE
WITWATERSRAND BASIN
AXIS OF
DEPOSITIONAL
SYNCLINE
ANTICLINE
HIGH
Legend

Figure 2.

THE STRUCTURE AND STRATIGRAPHY OF THE TRANSVAAL SEQUENCE

Structural Analysis of the Potchefstroom Synclinorium

Introduction

A structural investigation in a cratonic environment necessitates an examination of the regional setting of the younger formations relative to the older. Following this approach, an attempt was made to show that the present geometry of the Potchefstroom Synclinorium, as best outlined by the outcrop of the Black Reef Member is not a response to post-Transvaal tectonics, but has been in the process of evolution since pre-Witwatersrand times. Over this long period of time, it is suggested that several structural elements of a continuous but pulsating nature influenced the shape of the synclinorium, the final stage being the formation of the present-day arcuate structure. With reference to previous work on older strata within the limits of the synclinorium, and by interpreting structural and outcrop data from the Transvaal Sequence, the validity of the above hypothesis has been evaluated.

Tectonic Elements in the South-Western Transvaal and Northern Orange Free State during pre-Black Reef Times

The earliest manifestations of those crustal deformations which had an effect on the deposition of succeeding sequences, are displayed in the Witwatersrand Sequence. Figure 2 is a representation of the major positive and negative tectonic elements present during Witwatersrand times as deduced from isopach maps by Brock and Pretorius (1964a). The important features shown in this figure which directly or indirectly had an effect on Transvaal Sequence deposition, are as follows :

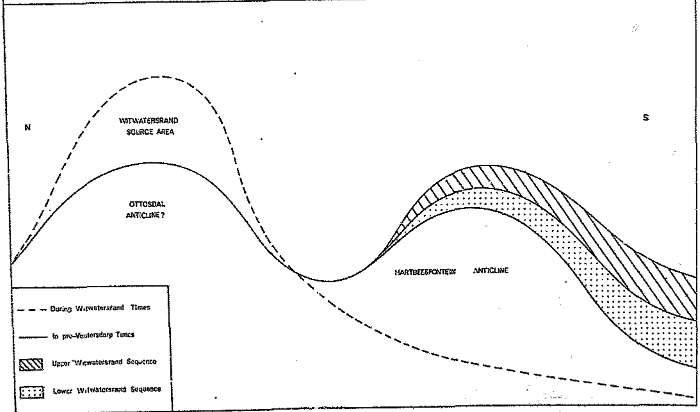
i. The presence of a positive source area to the north of Pretoria and the absence of the Johannesburg Dome at Witwatersrand times.

ii. The absence of the Hartbeestfontein Anticline (Figure 5) at these times, and the indications of the existence of a positive source area stretching north and south of Coligny (Brock and Pretorius, 1964a). The granite upwarp developed in this area, termed the Ottosdal Anticline (Figure 5), is probably a remnant of this source area. This linear exposure of basement granite, roughly parallel to the southern extension of the main axis of the Potchefstroom Synclinorium, disappears beneath Karroo and Transvaal sediments near Lichtenburg. It is considered likely that this basement upwarp did, in Witwatersrand times, extend eastwards with a strike parallel to the depositional axis of the basin and constituted the source area of the Witwatersrand Sequence to the north of Pretoria.

iii. The positive nature of the Potchefstroom Anticline during Witwatersrand time. It is noticeable that where an extension of this trend intersects the probable position of the Ottosdal Anticline, below Transvaal Sequence cover, a gravity low exists. The isopach data of Brock and Pretorius (1964a) suggests that the Vredefort Dome, lying on the Potchefstroom Anticline, was active during Witwatersrand times. The

HYPOTHETICAL NORTH–SOUTH SECTION OF TECTONIC ACTIVITY IN PRE-TRANSVAAL SEQUENCE TIMES

Figure 3



above authors proposed that a tectonically positive element to the south acted as a minor source area, as manifested in the occasional conglomerate horizons in Upper Witwatersrand sediments along the south-western edge of the basin.

iv. Structural lows in the Klerksdorp and Fochville areas where the syncline in the Vierfontein district and the transverse Carletonville Syncline intersect the main synclinal axis of the Potchefstroom Synclinorium, as existing during Witwatersrand times.

v. A major anticlinal trend to the east of Heidelberg, termed the Marievale Anticline by Papenfus (1964), which defines the eastern limit of the development of Transvaal strata within the Potchefstroom Synclinorium.

Structural investigations of a more detailed nature within the Witwatersrand Basin have been undertaken by numerous research workers. These merit brief mention at this stage, as they contain evidence of crustal deformations before or during the Witwatersrand Sequence deposition. Pretorius (1964), in an examination of the South Rand Goldfield, recognized a series of synclines and anticlines which, he considered, had been active during the processes of sedimentation. The majority of the more westerly of these trends, shown in Figure 5, were named after towns and farms on the West Rand. From west to east these are : the Doornpoort Syncline, the Middelvlei Anticline, the Krugersdorp Syncline, the Doornkop Anticline, the Roodepoort Syncline and the Palmietfontein Anticline. The Krugersdorp Syncline can be identified across the basin in the West Rand Goldfield where Toens and Griffiths (1964), with the aid of isopach data on the South Main Reef, recognized a similar control on sedimentation to that described by Pretorius (1964) in the South Rand area. During a study of the Vaal Reef in the Klerksdorp area, McLachlan (1968) constructed a structure contour map which outlined a north-easterly trending elliptical basin, the axis of which is parallel to that of the synclinorium. This structure is reported by Wilson and others (1964) to outline the greater portion of the area underlain by the Vaal Reef, and was thus probably active during deposition of this reef.

At the end of Witwatersrand sedimentation, uplift of the Johannesburg Dome and the Hartbeestfontein Anticline became pronounced, while the elevation of the more northerly Witwatersrand source area appears to have been less prominent at the time of outpouring of the Ventersdorp Lavas. As shown in the hypothetical cross-section (Figure 3), this uplift resulted in a trough-like feature being developed to the north of the Hartbeestfontein Anticline, into which lavas in excess of 2,500 metres, as indicated by drilling, were emplaced, so as to unconformably overlie Witwatersrand sediments. To the south of this anticline, as shown by the sub-outcrop pattern (Figure 4), and discussed by de Kock (1964), the lavas unconformably overlie Lower and Upper Witwatersrand sediments, particularly along the northern and north-western limb of the synclinorium. On the southern limb of the structure, the effect of the Vredefort Dome was considered to be more pronounced in Ventersdorp times than earlier, to the extent that Brock and Pretorius (1964a) suggested that the lavas never in fact covered the dome but occupy a moat around its periphery. Knowles (1966), during an investigation at Western Deep Levels gold mine, outlined structural culminations and depressions at the base of the Ventersdorp Contact Reef, to which he closely correlated the style of sedimentology and the mineralization. The longitudinal structural trends which were recognized are of particular significance, being roughly parallel to the

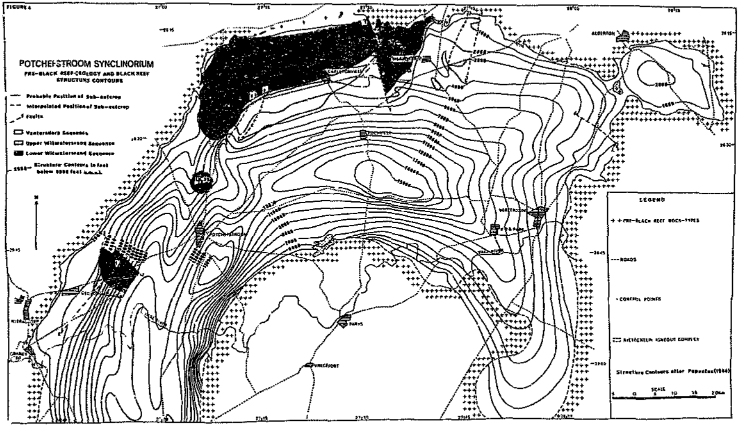


FIGURE 4
POTCHEFSTROOM SYNCLINORIUM
PRE-BLACK REEF GEOLOGY AND BLACK REEF STRUCTURE CONTOURS
Probable Position of Sub-outcrop
Interpolated Position of Sub-outcrop
Faults
Ventersdorp Sequence
Upper Witwatersrand Sequence
Lower Witwatersrand Sequence
Structure Contours in feet
LEGEND
PRE-BLACK REEF ROCK-TYPES
ROADS
CONTROL POINTS
SCALE
ALBERTON
PARYS

Hartbeestfontein Anticline.

An examination of the suboutcrop pattern in Figure 4, which has been extensively modified after Papenfus (1964), reveals a number of structural trends particularly along the northern and north-western limb of the synclinorium. To the west of Westonaria, Witwatersrand sediments suboutcrop below the Black Reef, while 5 km east of this town an upfaulted block of the same sediments occurs below the Black Reef. The rough parallelism of these two Upper Witwatersrand suboutcrops suggests that the faults shown bounding the latter may have been controlled by an anticlinal fold trend, with Ventersdorp lavas occupying the intervening syncline between this and the Upper Witwatersrand suboutcrop to the west of Westonaria. The change in strike of the latter Upper Witwatersrand strata, as shown in Figure 4, is considered to be related to the development of the Hartbeestfontein Anticline and major activity along the Krugersdorp Syncline in post-Witwatersrand times. The Lower Witwatersrand sediments, intersected below the Black Reef in the Borehole DC.39 to the north of Potchefstroom (Figure 4), surrounded by transgressive Ventersdorp Lavas, indicate a period of folding, followed by erosion, before deposition of the Transvaal Sequence.

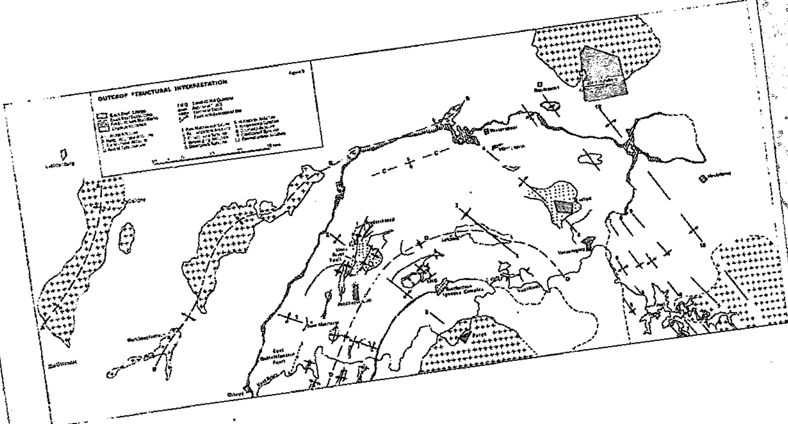
In summary, it can be noted that during pre-Transvaal periods of time, a number of tectonic elements are recognizable, which were more or less active at different stages. The more important of these elements, which have exerted a positive influence on the geometry of younger formations, are the Ottosdal Anticline, the Hartbeestfontein Anticline, and the Vredefort Dome. The Ottosdal Anticline was most active in pre-Witwatersrand times, the Hartbeestfontein Anticline in pre-Ventersdorp times, while the Vredefort Dome was apparently becoming increasingly active with time.

The Present Geometry of the Synclinorium

Having thus briefly discussed the tectonics affecting the underlying formations, it is now intended to trace these structures into the Transvaal Sequence. It is intended that detailed examination of borehole data and surface structural anomalies will outline the geometry of the synclinorium, as developed today, while in a later section it is hoped to show whether this geometry is a manifestation of post-depositional tectonics or of tectonic movements contemporaneous with the deposition of the Transvaal Sequence.

(a) Outcrop Structural Anomalies

An examination of the outcrop of the Transvaal Sequence and older formations in the Potchefstroom Synclinorium and surrounding areas reveals a remarkable series of interference structures. These have been formed by the superimposition of a number of periods of deformation, of which two are readily recognizable in outcrop. These two trends, termed the transverse and longitudinal by Pretorius (1964), are approximately at right angles to one another, in areas other than in the Westonaria district. Where the axial planes of the two trends approach the vertical, this superimposition has led to the formation of dome-and-basin structures with a circular to elliptical cross-section, analogous to the 'Type 1' interference structures of Ramsay (1967). 'Type 2' outcrop patterns described by Ramsay (1967) are also sporadically developed in those areas where the axial planes of the


OUTCROP STRUCTURAL INTERPRETATION

first folds were inclined, a typical example of which is present north-east of Potchefstroom (Figure 5). In addition to the above structures, numerous well-defined plunging synclines and anticlines are developed throughout the synclinorium.

Figure 5, which was prepared from the Geological Survey maps of the East and West Rand, reveals a number of the structures referred to above, many of which affected not only the Transvaal Sequence but also older formations, and which are at times traceable into the basement. The more readily recognizable longitudinal trends on the north-western limb of the synclinorium, largely concentric to the Vredefort Dome, except in the West Rand where the influence of the Johannesburg and Devon Domes (Button, 1968) becomes pronounced, are :

i. The main axis of the Potchefstroom Synclinorium, different to that existing at the time of Witwatersrand sedimentation (Figure 2).

ii. An anticlinal trend passing through the Johannesburg Dome and westwards along the Hartbeestfontein Anticline.

iii. A synclinal depression between the Hartbeesfontein and Ottosdal Anticlines to the south of Ventersdorp, filled with Ventersdorp lavas.

iv. An anticlinal trend to the north of Carletonville accounting for the thickening in dolomite outcrop in the West Witwatersrand area.

v. Numerous culminations and depressions, particularly around Potchefstroom and Frederikstad, indicating that secondary longitudinal trends exist, some of which are only locally developed (Figure 5).

The widespread development of longitudinal fold structures in the Klerksdorp - Potchefstroom area is related to more intense deformation in this part of the synclinorium than further east, and is associated with a narrowing of the outcrop width of the Transvaal Sequence.

Numerous transverse structural trends are recognizable throughout the Kaapvaal Craton (Pretorius, D.A., 1970, personal communication), assuming differing orders of magnitude and relative intensities. The most dominant trend within the area under investigation is the Potchefstroom Anticline, which includes the Vredefort Dome, and with which the interference structures to the north-east of Potchefstroom are associated (Figure 5). That this fold trend was active during or after deposition of the Transvaal Sequence is shown by the greatly exaggerated outcrop thickness of the Ongeluk Volcanics, as well as the domical structure piercing the volcanics and the outcrop pattern of the Daspoort Quartzite in this area.

Lower-order transverse structures developed in the synclinorium and recognizable in outcrop are :

i. The Palmietfontein Anticline, which is a second-order feature deforming rocks of the Witwatersrand, Ventersdorp, and Transvaal Sequences and connecting the Johannesburg Dome with the subsurface granite high to the south of Heidelberg. The latter also lies along the longitudinal positive trend including the basement high to the south of Parys (Figure 2).

ii. The Vereeniging Anticline is outlined : (a) by the plunging fold structure to the north-west of this town, termed the Vereeniging Dome by Jansen (1953a); (b) by the Ongeluk Volcanics around Evaton, which have an almost horizontal attitude; (c) by the dolomite protruberance through the

Pretoria Group sediments to the south of Westonaria, and (d) by the Lower Witwatersrand outcrop surrounded by Black Reef sediments to the west of Venterspost.

iii. The New Machavie Anticline, which deforms the base of the Pretoria Group around this town and has a plunge to the south-east in this area. The dome along this trend is a result of the intersection of two anticlines, in this case the New Machavie Anticline with a secondary positive longitudinal trend. On the south-eastern limb of the synclinorium, the same transverse anticline is seen to plunge to the north-west.

iv. A transverse synclinal axis is necessary to account for the basinal structure near Losberg. The exact positioning of this axis is not, however, possible at this stage due to the broad outcrop of the Magaliesberg Quartzite to the east of this town.

v. Evidence of a transverse syncline is shown in the development of closed, isolated basins of dolomite and Ongeluk Volcanics along an axis trending south-east from Roodepoort. This trend, termed the Roodepoort Syncline, was also recognized in the South Rand Goldfield by Pretorius (1964). An outcrop of Black Reef, piercing younger dolomite to the west of this trend, indicates an upwarp parallel to the Roodepoort Syncline (referred to as the Doornkop Anticline, after Pretorius [1964]).

Along the south-eastern limb of the synclinorium, a series of elongate domical and basinal structures is developed. To the north and south of the Vaal River in particular, a dominant longitudinal trend, refolded by weakly developed transverse synclines and anticlines, is apparent. As the dip of the Transvaal strata increases further northwards these structures become less obvious, before disappearing and only becoming noticeable again where overturning of the sequence has taken place to the west of the Rietfontein Igneous Complex. A complex outcrop pattern (Figure 5) reveals an en-echelon set of basinal structures, outlined by the Daspoort quartzite and off-set by a transverse upwarp. Longitudinal anticlinal trends are, in part, also deformed. The transverse anticline, which has displaced and warped the longitudinal syncline, does not deform Timeball Hill strata to the south. This is due to the steep dip of these sediments at the time of updoming to such an extent that the outcrop pattern shows no observable buckling.

After detailed outcrop mapping in the Lindequesdrift area, Jansen (1953b) postulated a series of isoclinal folds and brachy-structures to account for the many quartzite horizons developed in this area. Such structures are, however, completely out of character with the style of deformation in the synclinorium, particularly in the area under discussion, where no evidence of any major reduction in outcrop width is obvious. These observations led to a re-investigation of this area where a close examination of the Gatsrand Quartzites was carried out. The lithologic characteristics of the individual quartzite horizons were found to differ, while cross-bedding observations indicated that all horizons become younger in the same direction. It was thus not necessary to invoke tight folding related to a closely spaced series of longitudinal trends, but rather to conclude that a series of quartzite lenses are present. None of the minor domical structures developed to the east of Lindequesdrift indicates major compressional forces.

It has been observed that the transverse structural trends assume differing orders of magnitude. The same reasoning can be applied to the longitudinal trends with the axis of the synclinorium, defining the deepest portion of the basin, clearly the highest-order trend. Lower-order trends are also well-defined, while those which are impersistent define the weakest of the longitudinal deformations. Bearing in mind the above discussion, the relationship between the two fold trends can be determined from Figure 5. Where closed basin or dome structures are present, these are always elongated parallel to the longitudinal trend, even where the highest-order transverse folds have been superimposed on the lowest-order longitudinal. In the latter case, however, such as that developed where a domical structure pierces the Ongeluk Volcanics to the north-east of Potchefstroom, the outcrop pattern tends more and more towards a circular cross-section.

(b) Interpretation of Subsurface Data

(i) Contouring of Untreated Structural Data

The first composite structure contour map of the base of the Black Reef, prepared by Papenfus (1964) is reproduced in Figure 4, and shows that the effect of major faulting in post-Transvaal times was negligible. A number of features shown on this map are of relevance to the structural analysis of the synclinorium and warrant a brief review.

i. The steepening of the dip of the Black Reef in the Buffelsfontein area is due to the East Buffelsfontein Fault (Figure 5) which is post-Transvaal in age (Brock and Pretorius, 1964b).

ii. Longitudinal folds to the west of Potchefstroom are clearly shown on this map. The positioning of these structures further south, approaching the Vaal River, does not, however, agree with outcrop data (Figure 5), while the downwarp responsible for the development of the subsidiary Transvaal basin west of Potchefstroom appears from surface indications (Figure 5), to swing to the east through Frederikstad, and not to continue northwards as shown.

iii. The Potchefstroom Anticline occurs as a well-defined positive feature on the structure contour map.

iv. In the West Witwatersrand area and in most other regions of the synclinorium, the effects of the two fold trends are not evident in the figure, apart from a basinwards steepening in dip. This result indicates that contouring of untreated data is of minimal value in a structural investigation of this type.

v. Along the extreme northern limb of the synclinorium, in the vicinity of the Hartbeesfontein Anticline, the structure contours indicate folding along two synclinal axes trending north-east and north-west respectively.

vi. The Mooi River fault (Figure 5) to the west of Potchefstroom is not shown in Figure 4. This fault does, however, displace the Black Reef, although not extensively, as revealed by Borehole VH2, near Potchefstroom where duplication of strata has taken place due to thrusting from the south-east. Further to the north, in the vicinity of Frederikstad, field observations have revealed that thrusting has taken place from the north-west, such that brecciated chert overlies the lower Timeball Hill shales. Indications are that the last-mentioned fault probably post-dates that to the south.

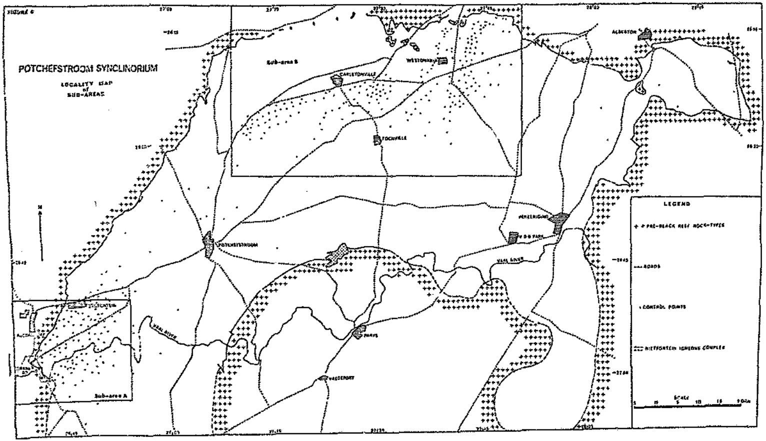


FIGURE 6
POTCHEFSTROOM SYNCLINORIUM
LOCALITY MAP
of
SUB-AREAS
Sub-area B
Sub-area A
CARLETONVILLE
FOCHVILLE
POTCHEFSTROOM
PARYS
VREDEFORT
VEREENIGING
ALBERTON
VAAL RIVER
LEGEND
PRE-BLACK REEF ROCK-TYPES
ROADS
CONTROL POINTS
VREDEFORT IGNEOUS COMPLEX
SCALE

(ii) Trend Surface Analysis

Having noted the limitations in contouring untreated structural information, it was considered necessary to subject the available borehole structural data to some form of mathematical treatment involving the preparation of derived maps (Krumbein and Sloss, 1963, p. 436). Trend surface analysis is the most popular of the methods available, and, according to Krumbein (1959), is "a procedure for separating the relatively large-scale systematic changes in mapped data from the essentially non-systematic small-scale variations due to local effects". In the map prepared by Papenfus (1964) (Figure 4), the regional or large-scale trend has the effect of masking all but the strongest local structural anomalies. Clearly, for untreated data, as the size of the area being contoured decreases and the number of control points per unit area increases, the local effect will become more and more pronounced. However, in an area the size of the Potchefstroom Synclinorium, it was considered that trend surface analysis would aid in separating the local from the regional components. The theoretical background behind trend surface analysis has been dealt with in detail by numerous authors, a short review of which is given in Appendix 1.

Selection and Treatment of Data

In addition to the five hundred boreholes which intersect the Black Reef in the Potchefstroom Synclinorium one hundred control points were obtained by transferring outcrop positions of the Black Reef from geological maps of the area onto 1/50,000 topocadastral maps and reading off the height above sea-level at localities marked along the outcrop. The latter source of data proved to be particularly useful for the southeastern limb of the synclinorium where borehole data are lacking. Values at all control points were converted to metres, above or below sea-level, to the base of the Black Reef, which along with the x and y co-ordinates for each point were entered on I.B.M. punching instruction sheets, each data point being given an identification symbol.

The structural investigation of the synclinorium by trend surface analysis was carried out in three stages determined largely by the distribution of the control points. In the first stage, one hundred and two randomly distributed control points covering the whole of the synclinorium were selected, using a random numbers table. Secondly, two areas containing high concentrations of control were outlined and subjected, in turn, to a detailed investigation. These two areas, referred to as sub-areas A and B (Figure 6) are situated in the Klerksdorp and Carletonville-Westonaria districts, containing one hundred and thirty-five and two hundred and five data points, respectively. To each set of data, the first- to fifth-order surfaces were fitted, the results of which are given in Table 3.

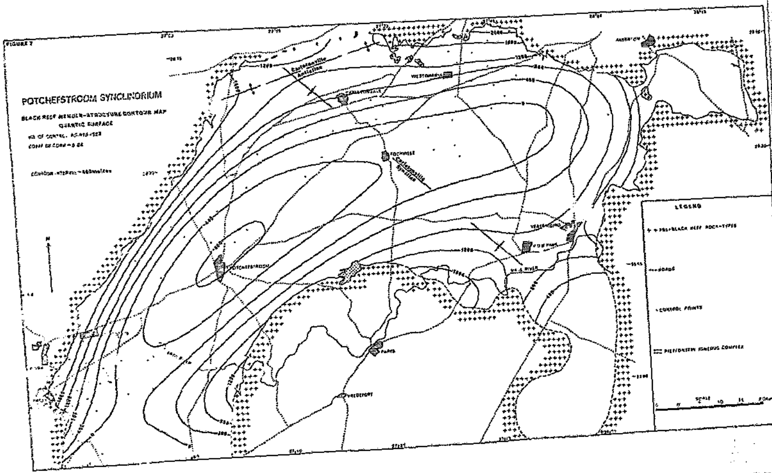


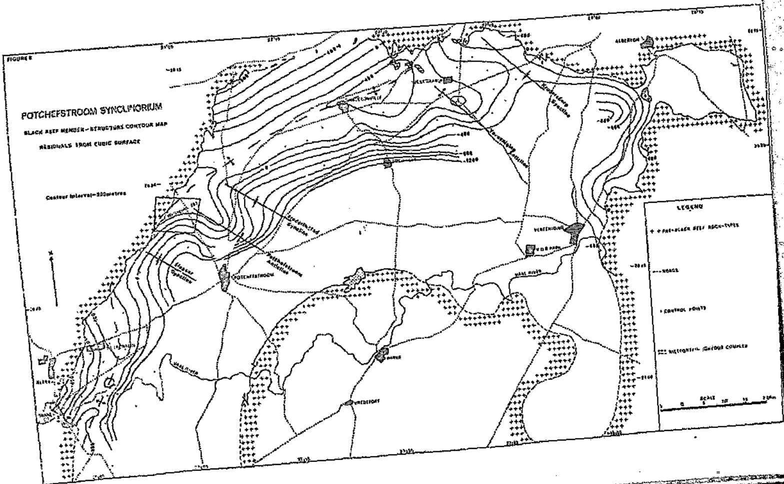
FIGURE 7
POTCHEFSTROOM SYNCLINORIUM
QUARTIC SURFACE
LEGEND
SCALE
WESTONARIA
FOCHVILLE
POTCHEFSTROOM
PARYS
VREDEFORT
Carletonville Anticline
Carletonville Syncline

TABLE 3

ORDER OF SURFACE	COEFFICIENT OF CORRELATION	PERCENTAGE VARIATION EXPLAINED BY SURFACE	INCREASE IN PERCENTAGE VARIATION EXPLAINED BY SURFACE
Linear	0.22	4.7	
Quadratic	0.58	33.3	28.6
Cubic	0.70	48.8	15.5
Quartic	0.84	70.2	21.4
Quintic	0.89	79.7	9.5
	TOTAL AREA		
Linear	0.85	74.6	
Quadratic	0.89	80.8	6.2
Cubic	0.94	88.2	7.4
Quartic	0.96	92.1	3.9
Quintic	0.98	95.5	3.4
	SUB - AREA 'A'		
Linear	0.89	79.4	
Quadratic	0.91	82.4	3.0
Cubic	0.91	83.3	0.9
Quartic	0.92	85.3	2.0
Quintic	0.93	86.2	0.9
	SUB - AREA 'B'		

Analysis of Results

An examination of Table 3 reveals a remarkably high percentage 'fit' for most surfaces. The low percentage variation explained by the linear surface of the total area is accounted for by the geometry of the structure. Results obtained (Table 3) indicate that the quintic and quartic surfaces are of particular significance, confirming the strong regional trend of the synclinorium suggested by Figure 5. The quartic surface (Figure 7), however, was chosen as being most representative of the trend, as the increase in percentage variation over the cubic explained by this surface was much greater than for the quintic over the quartic, and therefore contributed more towards explaining the total variation.


POTCHEFSTROOM SYNCLINORIUM
BLACK REEF MEMBER—STRUCTURE CONTOUR MAP
RESIDUALS FROM CUBIC SURFACE
POTCHEFSTROOM
VEREENIGING
ALBERTON
VREDEFORT
VAAL RIVER
LEGEND
CONTROL POINTS
SCALE

The most important features outlined in Figure 7 are :

i. The axis of the synclinorium wraps around much of the Vredefort Dome.

ii. A second order synclinal axis between the Potchefstroom and Vereeniging Anticlines, trending in a north-westerly direction, is referred to as the Carletonville Syncline and includes the Magaliesberg basin (Figure 5) to the east of Losberg. In the Vanderbijlpark area, the Carletonville Syncline is almost parallel to the main axis of the synclinorium, a fact noticed by Pretorius (1964) in the South Rand Goldfield. The former is also the dominant transverse syncline in the synclinorium, being the only structure of regional dimensions of this type.

iii. An anticlinal fold trend to the north of Carletonville, parallel to the main synclinal axis of the synclinorium. The position of this fold is probably not correct, as dip measurements shown on the Geological Survey map of the West Rand revealed its position to be just to the north of Carletonville. This inaccuracy in the positioning of the fold is due to poor, or absence of, control extending from south of Carletonville to the Hartbeesfontein Anticline and thus including the axis of the fold trend. Under such circumstances, the regional surface assumes the dip determined in areas of good control, projecting this plane through regions of poor control before attempting to 'fit' any further control points to the surface, which in this case lie on the Hartbeesfontein Anticline.

The remarkably high 'percentage fits' obtained in sub-areas A and B for the linear surfaces (Table 3) indicate that the latter approximate the true structure in these areas. The printed surfaces, which are not shown, indicate shallow dipping planes trending north-north-east and east-north-east in the two sub-areas A and B, respectively.

(iii) Mapping of Residuals

A series of maps using calculated residuals from each stage of the trend surface analysis was prepared. These are shown in Figures 8, 9, and 10 for the total area and sub-areas A and B, respectively. While in some cases the same structures as previously identified were again delineated, these maps serve to connect previously isolated outcrop structural anomalies (Figure 5), and to identify lower-order transverse synclines and anticlines. The residual maps thus give a more continuous representation of structural trends along the northern and north-western limb of the synclinorium. Allen and Krumbein (1962) found that where the trend surfaces were able to explain only a small percentage of the total variation, the residuals were highly significant, but where a percentage 'fit' of 80% was obtained, the residuals lost their geological significance. In the case of the data being analyzed in the present study, however, the residual maps prepared could be interpreted geologically with a great deal of confidence, even where percentage 'fits' of the order of 90% were obtained.

Interpretation of Maps

The map prepared for the total area, using the residuals from the quadratic surface, when considered in conjunction with Figure 7, delineates the major structural features of the synclinorium, certain of which have already been discussed. The fact that the Potchefstroom and Vereeniging Anticlines and the Carletonville Syncline, can be recognized from outcrop

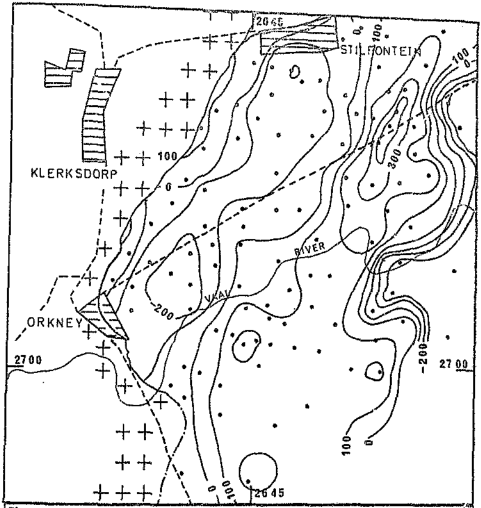


Figure 9

POTCHEFSTROOM SYNCLINORIUM

Sub-area A

Black Reef Member-Structure Contour Map

Residuals From Cubic Surface

Contour Interval - 100 metres • Control Points

+ + Pre- Black Reef Rock-Types -- Roads

N

Scale

1 0 2 4 6 Km

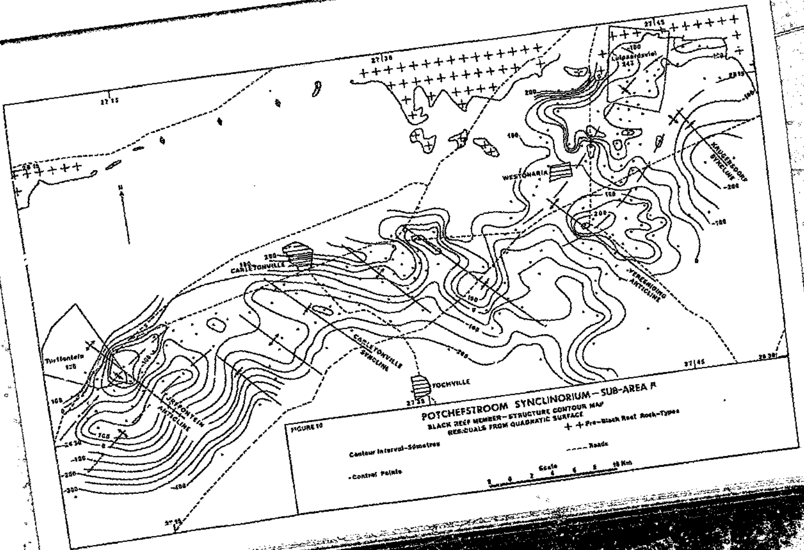


FIGURE 10

POTCHEFSTROOM SYNCLINORIUM — SUB-AREA A
BLACK REEF MEMBER — STRUCTURE CONTOUR MAP
RESIDUALS FROM QUADRATIC SURFACE

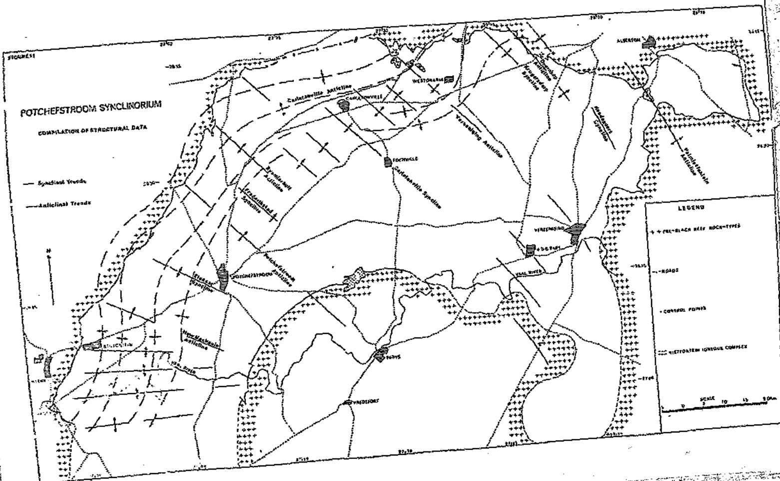
and be clearly outlined on the trend or residual map. points to these as being major transverse tectonic trends. The longitudinal anticline north of Carletonville (Figure 7) is a well-defined trend in Figure 8, extending across the northern limb of the synclinorium before swinging southwards and eventually crossing the Vaal River east of Orkney. As shown in Figure 8, the axis of this structure passes outside the limits of the synclinorium on the farm Welgegund 375, before bending southwards to assume a north-south orientation, in sympathy with the main axis of the synclinorium, when reappearing to the north of Stilfontein.

In addition to those structural trends already recognized, certain other features became readily apparent on the contoured residual map. A major negative residual trend was outlined to the east of Ventersdorp (Figure 8) which, on projection northwards, coincided with the Krugersdorp Syncline. The positive influence of the Johannesburg Dome was noted to the north-east of this syncline. Two structural lows, termed the Frederikstad and Eleazar Synclines, the latter being flanked on the south by the New Machavie Anticline, are developed to the north and south of the Potchefstroom Anticline, respectively. The effect of the Eleazar Syncline was to refold the longitudinal Carletonville Anticline, with a resultant bending of the latter in a north-westerly direction.

The fact that the transverse structural trends in the Carletonville and Klerksdorp districts are poorly defined in Figure 8, indicates that they are lower-order features which will become apparent only through a more detailed examination. For this reason, it was considered necessary to prepare residual maps from stages 2 and 3 of the trend surface analysis. The residual maps from the cubic and quadratic surfaces, for the sub-areas A and B respectively (Figures 9 and 10) were chosen as being the most statistically reliable, as the "increase in percentage fit" explained by these trend surfaces is the greatest. Numerous additional transverse and longitudinal trends can be identified in the latter figures.

In the Klerksdorp area (Figure 9), the longitudinal trends are particularly noticeable. A major structural low, trending north-north-east to south-south-west from Stilfontein to Orkney is flanked by two anticlinal trends. These structures are evident in Figure 9, due to the increased number of data points used in comparison with Figure 8. The transverse trends are not as distinct as the longitudinal, but two synclines and two anticlines are evident. These four trends and the more northerly New Machavie Anticline can be extended across the synclinorium to account for the outcrop pattern on the eastern limb in this area (Figure 5). The strike of the above transverse structures is seen to be rotated southwards when compared with the Potchefstroom Anticline. In the vicinity of the Vaal River the transverse syncline through Orkney appears to have an almost east-west strike.

On examination of the results obtained from the mapping of residuals in the second of the sub-areas (Figure 10), it is found that the transverse trend assumes major importance. The Vereeniging Anticline and Carletonville Syncline are clearly defined, with the Turffontein Anticline on the western boundary of this area also recognized. The latter is represented by an elongate domical structure trending north-east to south-west, again emphasizing the relative importance of the longitudinal trend. Less prominent synclinal and anticlinal fold axes between the Rysmierbult Anticline and Carletonville Syncline and between the latter and the



POTCHEFSTROOM SYNCLINORIUM
COMPILATION OF STRUCTURAL DATA
Synclinal Trends
Anticlinal Trends
LEGEND
PRE-BLACK REEF ROCK-TYPES
ROADS
CONTROL POINTS
SCALE
ALBERTON
WESTONARIA
CARLETONVILLE
FOCHVILLE
VEREENIGING
POTCHEFSTROOM
PARYS
VREDEFORT
VAAL RIVER
Carletonville Anticline
Carletonville Syncline
Vereeniging Anticline
Potchefstroom Anticline

Vereeniging Anticline are also apparent in Figure 10. To the north of the above structure an elongate structural low exists, coinciding fairly closely with the Ventersdorp lava suboutcrop in this area (Figure 4). This suggests that the lavas may have been preserved from erosion in a syncline instead of in a graben. In the Westonaria district a northwards swing of the longitudinal trend is evident. A syncline trending north-north-east passes through this town and maintains the same strike northwards into the Luipaardsvlei area. Anticlinal trends are developed on both sides of the syncline, coinciding closely with the sub-outcrop pattern (Figure 4). Where the Vereeniging Anticline intersected the south-easterly of these two anticlines, a domical structure was formed which occurs directly below the dolomite dome piercing Pretoria Group sediments (Figure 5). This longitudinal trend displays a marked change in strike to the south-east of Luipaardsvlei, as a result of refolding by the Krugersdorp Syncline, to assume the more normal east-west strike further to the east.

Compilation of Structural Data

The structural analysis of the Potchefstroom Synclinorium, particularly along the north-western limb, has revealed the presence of transverse and longitudinal fold trends, representing at least two periods of deformation. As previously discussed, the deposition of Witwatersrand and Ventersdorp sedimentary strata was structurally controlled, as recognized in the Klerksdorp, South Rand, West and Far West Rand areas by McLachlan (1968), Toens and Griffiths (1964), Pretorius (1964), and Knowles (1966), respectively. Structure contours at the base of the Black Reef as shown in Figures 8, 9 and 10 clearly outline the same longitudinal synclinal fold trend to the east of Klerksdorp and the Krugersdorp and Carletonville transverse synclines in the West and Far West Rand areas, respectively. The longitudinal trends recognized by Knowles (1966) are not obvious in Figure 10, but an extension of the longitudinal synclinal structure, recognized to the east of Westonaria and in the Turffontein district to the west, through Western Deep Levels, coincides with the longitudinal depression recognized by that author.

A compilation of all structural data referred to before, is given in Figure 11. It is apparent that the longitudinal folding preceded the transverse, as shown by the deformation of the former by the Krugersdorp and Eleazar transverse synclines. Further evidence for this relationship is provided by outcrop patterns within the synclinorium. The arrowhead structure, outlined by the Ongeluk Volcanics (Figure 5) to the north-east of Potchefstroom is a 'Type 2' interference structure of Ramsay (1967). The transverse Potchefstroom Anticline, representing the later period of folding was superimposed on the earlier longitudinal anticline, the latter having an ial plane dipping to the south-east. To the north-east of the arrow-head, refolding along a transverse synclinal axis is also evident (Figure 5). Despite being of a rather complex nature, the interference structures west of the Rietfontein Igneous Complex (Figure 5) also indicate that the transverse folding post-dates the longitudinal, the former being active a time when the Transvaal sediments had, in part, an almost vertical attitude. To the south of Vanderbijlpark, a downwarp is imprinted on the broad structural high (Figure 2) by the transverse Carletonville Syncline, resulting in a saddle-like structure.

In addition to outlining the major longitudinal axis of the synclinorium, Figure 11 also shows the behaviour of the transverse fold axes. From south of Orkney to Potchefstroom, a fold pattern radial from the Vredefort Dome is evident. Further to the north-east, the axes of the folds are parallel to the Potchefstroom Anticline maintaining a constant wave-length as far as the Vereeniging Anticline. East of this structure, a variable wave-length is evident, accompanied by a bending of the fold-axes as the South Rand Goldfield is approached.

The Malmani Dolomite Formation

The Dolomite Controversy

(a) Introduction

Numerous ideas regarding the mode of origin of dolomite have been expressed, with the two most popular, but opposing, schools of thought postulating the theories of dolomite being formed by primary precipitation or secondary replacement. The problems of sedimentary dolomites are centred mainly around the possible conditions of precipitation of primary dolomite and/or the source of the solutions to form secondary dolomite. A review of these problems is presented before considering the genesis of the Malmani Dolomite in the light of the following discussion.

(b) Primary vs. Secondary Origin

The classification of dolomites, according to their mode of origin, was proposed by Weber (1964), who noted that primary dolomites display excellent stratification, have a very fine to cryptocrystalline and uniform grain-size, and contain no detectable calcite or fossil remains. Secondary dolomites, on the other hand, display a coarser, less uniform grain-size and generally contain euhedral dolomite rhombs. Faunal remains and relict structures and textures are considered to typify the secondary variety.

Calcium and magnesium carbonates have been, and are being, formed from natural waters in or on the lithosphere, certain of which are more likely to precipitate dolomite than others. Having indicated that substantial amounts of magnesium must be added to limestones to form pure dolomite, Ingerson (1962) noted that ground-waters are particularly deficient in this cation, with the only logical source of magnesium-bearing solutions being ocean waters. It thus seems desirable to confine the discussion of dolomite formation to present-day oceanic environments, before attempting to apply these findings to older deposits. The dangers of drawing an analogy between present-day carbonate precipitation, and that in older formations, was appreciated by Chilingar (1953) when he noted that Ca/Mg ratios for dolomitic limestones decreased with age of the sediments, indicating a calcium enrichment in more recent times. This was interpreted as being due to a selective return of calcium to the lands, and not as resulting from a longer period of time during which magnesium could replace calcium. There is rather a preferential weathering of calcium over magnesium in the sediments and a gradual increase with time of Ca/Mg ratios in solutions contributing to the sea.

Following an exhaustive review of available literature, Toens (1966) concluded that dolomites may originate through one of four processes :

that with a decrease in depth and distance from shore there was a sympathetic relationship to that noted for increasing temperatures. This observation was also recorded by Marschner (1968) as a decrease in $CaCO_3$ content from the base to the top of any stratigraphic section, leading him to the conclusion that salinity within the depositional environment increased with time.

All evidence cited points to a close relationship between an increasing concentration of magnesium corresponding to a higher salinity, a rising pH, and an increase in environmental temperatures. Also, both the Australian and Bahaman examples discussed contain primary dolomite in shallow water to sub-aerial environments, suggesting the possible influence of evaporation in dolomite formation. The occurrence of gypsum in close association with different carbonate minerals on Bonaire, in the Netherlands Antilles, as reported by Deffeyes and others (1965), supports this suggestion. It can be concluded that the most favourable environment for dolomite formation is in the littoral zone, but that, as illustrated in the examples referred to, primary dolomite is quantitatively unimportant. These observations tend to argue against a primary chemical or organic mode of origin for great thicknesses of dolomite, such as is developed in the Malmani Dolomite Formation. A secondary origin involving inorganic magnesium enrichment or dolomitization is more acceptable.

(c) Dolomitization

The fact that secondary magnesium enrichment is necessary to form dolomites seems highly probable, but, the time of dolomitization is a matter of some conjecture.

Hsu (1966) considered that dolomitization takes place through a combination of two processes :

i. The presence of evaporite beds in carbonate sequences is indicative of arid conditions during which magnesium in sea water may have been concentrated. The importance of evaporites was recognized in the Netherlands Antilles by Deffeyes and others (1965), where calcium carbonate and gypsum were precipitating from sea water, producing dense brines having Mg/Ca ratios in excess of 30:1.

ii. During times of regression, shelf deposits can be exposed, setting up hydrodynamic heads which will induce the motion of brinal solutions through the exposed sediments. Studies in the Antilles (Deffeyes and others, 1965) showed that downward drainage of high-magnesium brines resulted in the dolomitization of large areas cutting across the bedding. Field evidence indicated that the dolomitization was produced by the flow of dense brines from supratidal areas.

Whether evaporation is required to generate high-magnesium brines may be questioned. In accordance with the findings of Chilingar (1953), the possibility exists that in earlier geologic times the magnesium content of sea waters was sufficiently high for dense brinal solutions to develop without evaporite formation. Fairbridge (1957), in fact, made no mention of evaporites in considering that dolomitization began to form initially very early in diagenesis, being of penecontemporaneous nature. This he suggested may be due to the instability of both aragonite and high-magnesium calcite in the presence of magnesium-rich solutions. Interstitial waters, highly concentrated in magnesium, were reported from both South Australia and the Bahamas by Alderman and Skinner (1959) and Shinn and others (1970), respectively, suggesting that even these so-called primary dolomites were formed by the pene-contemporaneous replacement of calcite by dolomite as outlined by Deffeyes and others (1965), as follows :

$$2CaCO_3 + Mg^{2+} + CaMg(CO_3)_2 + Ca^{2+}$$

The ideas of Fairbridge (1957) appear to have particular application to extensive deposits of dolomite. Such an occurrence constitutes the Malmani Dolomite Formation where, in the area under investigation, a complete absence of limestone was noted. It is most difficult to visualise a late magnesium-rich solution percolating through 4,000 feet of limestone causing complete alteration. There is no evidence of the decrease in volume which would accompany dolomitization of consolidated limestone, nor is there any sign of the released calcium in the form of calcite veins or concretions. A more logical explanation would involve a dynamic cycle of pene-contemporaneous dolomite formation. Initially, during the precipitation of limestone, the solution would have been enriched in magnesium until at a critical Mg/Ca ratio dolomitization of earlier calcium-rich carbonates would have taken place, not only in the immediate supratidal environment but also further basinwards as the brinal solutions migrated. As the released calcium was taken into solution and the equilibrium Mg/Ca ratio of the original sea water regained dolomitization would have ceased. At this stage a new cycle, beginning with limestone deposition, would have been set in motion.

Constituents of Carbonate Rocks

(a) Introduction

All sediments can be considered as a response to two interacting systems, although one, under exceptional conditions of sedimentation, may be completely masked by the other. An autochthonous system, that produces sediments within the sea itself by chemical or biological processes, can be distinguished from an allochthonous system that brings sedimentary particles into the sea from beyond its limits (Shaw, 1964, p. 14).

In a succession of rock-types, such as is developed in the Malmani Dolomite Formation, composed mainly of carbonate constituents, the autochthonous pattern was clearly the most dominant. Those processes bringing material into the basin of deposition were, by comparison, much weaker, such that the only true allochthonous sediments present are thin carbonaceous shale horizons and minor quartzite lenses. It is intended at this stage to discuss the carbonate sediments within the Malmani Dolomite in detail, these being the most important autochthonous constituents present. The inclusion of chert within this binary sedimentary system, which bears a direct relationship to its origin, will be reviewed in a later section, as will be the nature of the allochthonous sediments that are present.

(b) Classification of Carbonate Rock Constituents

An analogy between clastic and carbonate sediments, based on similar textural relationships, was made by Folk (1959). A full particle-size range, with which a cementing medium is often associated, can be recognized in each group of sediments.

Folk (1959) classified the components of sedimentary carbonate rocks into two groups, namely, orthochemical and allochemical. Orthochemical constituents are essentially normal chemical precipitates, formed within the basin of deposition and which have been subjected to little or no transportation. Two types of orthochemical constituents are recognized :

i. Microcrystalline Calcite (Micrite).

Rapid chemical precipitation is thought to have resulted in the formation of micrite which occurs as crystals varying in size between 1 and 5 microns. With later settling to the bottom, infilling of voids between coarser constituents results in a similar texture to that developed in argillaceous sandstones.

ii. Sparry Calcite Cement (Sparite)

Sparite takes the form of a pore-filling cement, distinguished from micrite by its well-defined outline and coarser size, often approaching 10 microns or more in diameter.

Allochemical constituents are those components that formed by chemical precipitation within the basin of deposition, but which have generally suffered some later transport. Four types of allochems are recognized.

i. Intraclasts

These consist of pieces of weakly consolidated carbonate sediment that have been torn up and redeposited by currents. They vary in size from fine-sand to pebbles or boulders.

ii. Pellets are rounded and well-sorted aggregates of microcrystalline calcite varying in size between .03 to .20 mm and thought to represent fecal pellets of worms or other invertebrates.

iii. Oolites

A detailed discussion of oolites follows later.

iv. Fossils

Fossils are important constituents of many limestones, but as true allochemical components are not of significance in early Precambrian carbonate rocks.

(c) The Effects of Recrystallization

On recrystallization of carbonate rock-types, primary textures become somewhat modified or destroyed. In its early stages, this process is probably closely related to dolomitization. Three stages of recrystallization or 'neomorphism' have been recognized by Folk (1965) :

i. During early diagenesis, 2-micron needles or plates of primary micrite are converted to subequant polyhedra blocks of the same size.

ii. Further diagenesis results in the formation of microspar which has an average grain-size between 6 and 30 microns but characterized by a great uniformity in size between these two extreme values. Microspar forms by recrystallization of earlier neomorphic micrite, fine-grained intraclasts and pellets while oolites and sparry calcite are seldom affected.

iii. In 'freakish limestones' neomorphism may progress further, with recrystallization of all primary carbonate constituents except coarse intraclasts and oolites, producing pseudospar that may closely approximate normal pore-filling calcite in appearance. Diagnostic criteria for distinguishing between the two are the transection of allochems by pseudospar and the presence of ghost allochems. Also, the presence of loosely-packed allochems in a sparite cement argues against a primary origin for the latter. For sparry calcite to form as a cement, pore-space, supported by some means, must have been present. The most logical support is a close-packing of allochems, such that, if a loose-packing is developed, a complete recrystallization of all allochems, other than those visible, can be inferred. Similar crit ia can be used to distinguish fine-grained sparry cement from microspa..

The Malmani Dolomites

In the Malmani dolomites, the recognition of each type of allochem is extremely difficult. Coarse-grained intraclasts are found, although only sporadically. These have given rise to intra-formational conglomerates (Plate I, A). Owing to the marked degree of recrystallization, fine-grained intraclasts and pellets have seldom been preserved. If the only origin of the latter is fecal, as proposed by Folk (1959), pellets would not be present in the Malmani Dolomite. Other allochems, most notably oolites, are widely distributed but fossils are absent, apart from different types of algal stromatolites. For this reason, fossil fragments are not an important constituent of the dolomites.

Almost all dolomites in the Malmani Dolomite Formation are of the 'freakish limestone' type (Folk, 1964), as a result of their general coarse-grained nature. Micrite and sparite, as defined by Fol (1959), are not present. Only the coarsest variety of microspar has been identified in the dolomites studied .y the present author. Four dominant grain-sizes were recognizably related to the degree of recrystallization. These have been termed microspar (.02 - .03 m.m.), recrystallized microspar (.07 - .10 m.m.), pseudospar (.30 - .40 m.m.), and recrystallized pseudospar (> .60 m.m.). On a macro-scale, the microspar products have a dark colour while the pseudospar varieties have a white colour.

The varieties of individual textural types of dolomite in the Malmani Dolomite Formation are innumerable but four groupings, related essentially to degree of recrystallization, are recognizable :

(a) Homogeneous Dark-Coloured Dolomite

This dolomite (Plate I, B), which most closely resembles the primary carbonate rock-type, contains ghost relicts of intraclasts which have an average grain-size of .25 mm. The matrix and intraclasts consist mainly of microspar, although later neomorphic effects have resulted in the development of recrystallized microspar, randomly scattered throughout the rock. It is apparent that the microspar was formed at the expense of micrite and fine-grained intraclasts, while no evidence exists to suggest that sparite was an original constituent of the rock.

(b) Variegated Dolomite

As recrystallization increased, all microspar was converted to recrystallized microspar. The appearance of pseudospar and carbon porphyries, at this stage caused the rock to have a variegated or mottled appearance (Plate I, C). The development of porphyritic textures has been observed to be most pronounced in massive to thickly-bedded dolomites. The effect of this increased recrystallization on finely-bedded dolomites was to develop alternate light- and dark-coloured bands (Plate I, C), due to differential recrystallization within individual horizons. All fine-grained intraclasts and pellets were destroyed at this stage.

(c) Recrystallized Dolomite

This dolomite represents the most intense degree of recrystallization, being uniformly light in colour (Plate I, D) and consisting predominantly of pseudospar and recrystallized pseudospar, with occasional remnants of recrystallized microspar. In extreme examples of recrystallization, all traces of primary structures, including bedding, have been destroyed.

(d) Veined Dolomite

Although not widespread, this rock-type is most conspicuous where developed. As shown in Plate I (E), a dark-coloured dolomite is cut by sharply-defined light-coloured veins. The matrix consists of recrystallized microspar while the veins are composed of recrystallized pseudospar, also dolomitic in composition, with crystals up to .80 mm in size. The contacts between the matrix and veins are generally very sharp, with the grain-size of the recrystallized pseudospar appearing to increase towards the centre of the vein. Both these features are, according to Stauffer (1962), indicative of open-space filling of a brecciated host-rock.

(e) Genesis of the Dolomites

The mechanism of formation of different dolomite types was discussed by Folk (1964), who concluded that neomorphism is either porphyroid or coalescent. Porphyroid recrystallization involves growth of a few large crystals in a static groundmass. Coalescent neomorphism takes the form of a gradual enlargement, maintaining a uniform crystal size at all times. Clearly, the end products resulting from each process are indistinguishable.

The genesis of the different types of dolomite in the Malmani Dolomite Formation can be related to the above processes. While the textural patterns are comparable in each case, the crystal sizes differ considerably in magnitude. A progressive increase in neomorphism has resulted in the formation of the dark, mottled and recrystallized dolomites. The microspar matrix of the dark-coloured dolomites represents either a complete fusion of porphyries, or is a product of coalescent neomorphism. With an increase in recrystallization, porphyries of recrystallized microspar have formed as the second component of the dark-coloured dolomite.

Eventual fusion of the porphyries has resulted in the development of a uniform matrix of recrystallized microspar. A rejuvenation of porphyroid neomorphism has led to the formation of light-coloured pseudospar crystals, partly responsible for the mottling effect in the second type of dolomite. The carbon mottling is considered to have been caused by some metasomatic process, as discussed by Young (1934a), involving migration and concentration of this element from its initial disseminated state in the dolomite. Complete fusion of pseudospar porphyries has never taken place. As a result of this even the most extreme example of neomorphism, as represented by the recrystallized dolomite, still contains recrystallized microspar. This dolomite is composed predominantly of pseudospar, while a later porphyroid neomorphism has developed scattered recrystallized pseudospar crystals.

The origin of the veined dolomite is somewhat problematical in that the vein material, while meeting the requirements of an open-space filling, is much coarser than normal sparite. No obvious explanation is forthcoming, save to note a resemblance in outward appearance to mud-cracks, cemented by a second generation carbonate infilling.

As regards the causes of recrystallization, Folk (1964) admitted that nothing concrete could be said. The same author reviewed possible environmental causes such as the salinity of the environment and the clay content of the limestone or dolomite, but concluded that more research was necessary before any conclusions could be drawn. Irrespective of the cause of recrystallization, there does exist within the Malmani Dolomite, definite zones having a predominance of certain dolomite types. This phenomenon requires an explanation and will be enlarged upon when the stratigraphic column for the Malmani Dolomite is constructed in a later section.

Carbonaceous Shales within the Malmani Dolomite

In order that carbonaceous shales can form, an environment of deoxygenation and restricted circulation is necessary. Under the resultant anaerobic or euxinic conditions there prevails a reducing environment in which organic matter, ultimately responsible for the black colouration is preserved. The reducing conditions required for black shale deposition are encountered in numerous environments and are controlled largely by the morphology of the basin of deposition. Rich (1951) argued as regards a deep-water origin, that a density stratification, related to salinity differences, inhibits circulation. Ruedeman (1934) came to a similar conclusion as regards carbonate-black shale associations. He suggested that in deep-lying regions, at depths of greater than 3,000 metres, carbonates go into solution, and only a shaly fraction remains. Both of the above hypotheses postulate deep-water conditions such as are only obtained in geosynclinal environments or marginal seas (Krumbein and Sloss, 1963, p. 416).

While agreeing that carbonaceous shales can form in deep-water environments, Krumbein and Sloss (1963, p. 566) proposed that euxinic conditions are also characteristic of lagoons cut off from the main body of the sea. Furthermore, they point out that, in contrast to the thick accumulations associated with greywacke assemblages, the lagoonal black shales tend to be relatively thin, although they may cover extra-ordinarily large areas. In discussing allochthonous sedimentation in epeiric seas, Shaw (1964, p. 37) considered that, even at the strand, significant wave action may not have existed. He noted black shale beds at the base of stratigraphic sections in many parts of North America, which contained little evidence of agitation. These were, however, clearly strand-line deposits, as they were the first deposits of a transgressing sea. Shaw (1964, p. 47) also mentioned the occurrence of coarse clastics in more shoreward environments, with carbonates developed basinwards of the black shales.

Within the Malmani Dolomite, the carbonaceous shales tend to be finely bedded, but with no evidence of sedimentary structures such as cross-bedding, ripple marks, or mud-flake horizons which typify shallow-water environments. However, in an epeiric basin such structures are likely to be rare or absent, due to the low energy within the depositional environment suggested for carbonaceous shales by Shaw (1964, p. 37). From the above evidence it is not possible to distinguish between a shallow- or deep-water origin for the black shales within the Malmani Dolomite. That the dark colouration is due to the organic content of the shales cannot be doubted, as the isotopic ratios of carbon, determined by Hoering (1961-62), favour a biogenic origin.

Detailed microscopic examination and x-ray diffraction determinations have revealed that, apart from carbon, the shales are composed of quartz, variable amounts of dolomite, and different clay minerals. The type of clay mineral within the stratigraphic column is found to vary with height. Samples near the base of the Malmani Dolomite contain both illite and kaolinite, the latter diminishing rapidly with height, until, from about 200 feet above the base to the top of the column, illite is the only clay mineral present. Under variable climatic conditions, different clay minerals are known to form (Grim, 1962, p. 517-518). Kaolinite only develops in fairly humid environments where total leaching of the alkali and alkali-earth metals is achieved. With less leaching, clay minerals such as illite are preserved. These observations indicate the existence of humid conditions at the commencement of Malmani Dolomite times, which were rapidly becoming more arid.

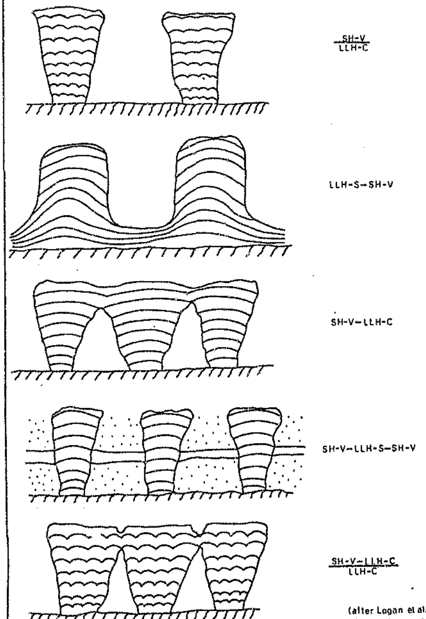
Algal Stromatolites

(a) Introduction

Detailed descriptions of algal stromatolites, particularly in the Griqualand West area, were given by Young (1932, 1940, and 1943) and by Young and Mendelssohn (1948). Two major types of algal stromatolites were recognized, namely those having domical and those having columnar geometries, with gradations between the two also developed. The sizes of the stromatolitic structures were considered to be controlled by the amount and size of sediment influx. The more material introduced, the larger the structure, except where complete smothering took place. The role of algal stromatolites is principally that of binding of influx sediment which had been derived from the reworking of older calcareous formations. After comparing stromatolitic rocks in South Africa with modern sediments in the Bahamas, Young (1934) concluded that "low-lying coastal flats under ambiguous condition[illegible] those of land and water" most favoured algal growth. Based to [illegible] extent on the environmental significance of algal stromatolites. You[illegible] [illegible]) extended his earlier

COMPOUND ALGAL STROMATOLITES

Figure 14



(after Logan et al, 1964)

observations from the Campbell Rand Series to the Dolomite Series of the Far West Rand, outlining the conditions of deposition of the 'series' in the two areas.

(b) Classification of Algal Stromatolites

The first classification of algal stromatolite structures based on their geometric forms was proposed by Logan and others (1964). It is essentially a descriptive, as opposed to generic, classification, related to the basic geometric unit, the hemispheroid, from which most stromatolites are built. Oncolites, which are built up of spheroids, are also considered as a type of stromatolitic structure.

Referring to Recent algal stromatolites and oncolites, Logan and others (1964) recognized three main arrangements of the basic geometric units :

i. Type - LLH, laterally linked hemispheroids - Collenia Structure

A further subdivision into Mode 'C', with close lateral linkage and Mode 'S', with spaced lateral linkage of the hemispheroids, was proposed.

ii. Type - SH, discrete vertically stacked hemispheroids - Cryptozoon Structure

Depending on whether the hemispheroids had a constant or variable basal radius, Modes 'C' and 'V' respectively were distinguished.

iii. Type - SS, spheroidal structures

Compound algal stromatolites (Figure 14) containing both collenia and cryptozoon structures, are also present in Recent environments.

Modern algal stromatolites are found to be restricted to certain environments, suggesting that, by recognition of fossil stromatolitic structures, ancient depositional environments can be interpreted. Numerous authors, notably Black (1933) in the Bahamas, and Logan (1961) in Western Australia, recognized that algal stromatolites form in the intertidal or littoral zone and may occasionally develop in the low-supratidal environment.

Logal and others (1964) proposed a three-way subdivision of the intertidal zone, each environment containing a characteristic geometric algal structure :

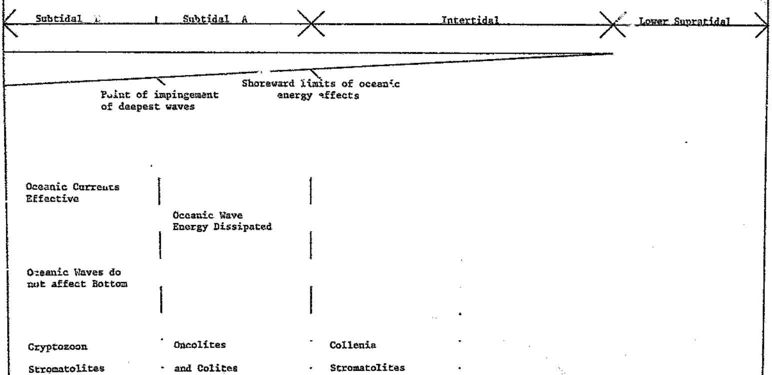
i. Type - LLH structures infer protected intertidal mud flats where wave action is slight. A similarity can be noticed between these structures and the domical stromatolites described by Young (1940).

ii. Type - SH structures are considered to be indicative of exposed intertidal mud flats, where the scouring action of waves prevent growth of algal mats between stromatolites. In their simplest form, these structures approach the columnar stromatolites described by Young (1940).

iii. Agitated shallow waters below low-water mark, in low intertidal areas, are inferred by the presence of oncolites of the Type - SS.

FIGURE 15

DISTRIBUTION OF MECHANICAL ENERGY IN AN EPEIRIC SEA



(Modified after Shaw, 1964)

The formation of the different algal structures is dependent essentially on energy differences within the depositional environment. In an epeiric sea, the optimum energy requirements of each type of algal structure occur. The distribution of the major sources of mechanical energy in an epeiric sea is shown in Figure 15, modified after Shaw (1964, p. 43), in which the three environments outlined by Logan and others (1964) can be recognized. In this model, Type - LLH stromatolites are developed nearest the strand, followed basinwards by Type - SS and Type - SH algal structures respectively. Thus, a stromatolite facies, isochronous in character (Krumbein and Sloss, 1963, p. 365), is developed.

With reference to Figure 15, a brief explanation of the stromatolite facies can be given. Collenia stromatolites develop nearest the shore where wave action is slightest, grading basinwards into the higher energy oceanic wave environment, under which conditions oncolites will form. Contrary to the ideas of Logan and others (1964), the author considers conditions basinwards of the impingement of deepest waves to be optimum for the development of Cryptozoon stromatolites. This proposal is supported by the findings of Playford and Cockbain (1969) who recognized columnar stromatolites as belonging to a subtidal fore-reef facies in Australian Devonian sediments. Water depths, although deeper than in the above environments, are still shallow and have active oceanic currents. In such an environment, in which oceanic waves do not affect the bottom, delicate stromatolite structures of the type shown in Plate IV (A and B) will not be destroyed, while upward growth in search of light will prevent the formation of laterally linked hemispheroids. Also, the oceanic currents, as shown by the presence of limestone detritus (Shaw, 1964, p. 43), are sufficiently strong in this shallow subtidal environment to promote growth of columnar stromatolites.

(c) Algal Stromatolites within the Malmani Dolomite

In this discussion it is not intended to give detailed descriptions of the algal stromatolites, since this has been covered in detail by Young in his papers between 1932 and 1948, but rather to consider their environmental significance by comparison, where considered valid, with the findings of Logan and others (1964). Within the Malmani Dolomite three distinct types of algal stromatolites are recognizable. These can be classified according to the scheme devised by Logan and others (1964).

i. Collenia : Type - LLH

The Collenia stromatolites in the Malmani Dolomite are most commonly domical in outline, with two varieties, differing significantly in size, being found. The larger of the two (Plate II) is up to 2 metres in diameter and height, often containing minor parasitic domes. A much smaller domical stromatolite (Plate III) which is seldom greater than 5 cm in diameter or height, is also developed. The latter approaches very closely in character the algal laminated sediments described by Davies (1970) from Shark Bay, Western Australia. In the field, the two types of domical stromatolites generally occur in close proximity, indicating somewhat similar environmental conditions during their formation. However, based on the argument that the size of the stromatolite is proportional to the amount and size of sediment influx, it is concluded that the smaller Collenia structures developed nearest the strand, in an epeiric sea where lower energies existed, than further basinwards (Figure 15). Also, the small-scale structures generally have the mode 'S' configuration, indicative of very slight wave action that allowed algal growth in the interstructure spaces. A somewhat disturbing fact, for which no explanation can be offered, is the absence of domical stromatolites, gradational in size between the two extremes discussed.

ii. Cryptozoon : Type - SH

Numerous examples of Cryptozoon stromatolites can be recognized in borehole cores, despite the fact that a true 3-dimensional impression is seldom obtained. As shown in Plate IV (A and B) these structures vary in size, as determined by the basal radius of the hemispheroid, and in type or complexity, as lateral spaced-linking between hemispheroids occurs sporadically up the column. The latter phenomenon is considered to be due to periodic sediment infilling of intercolumnar spaces.

Two Cryptozoon varieties with different structural formulae are illustrated in Plate IV.

A. SH - C with a basal radius approaching 2 cm.

B. SH - C + LLH - S + SH - C with a basal radius of 1 cm.

The different Cryptozoon types generally occur in close association in a stratigraphic section, although being indicative of different energy conditions. The stromatolitic structure shown in Plate IV 'A' is clearly a deeper water response than that shown in 'B'. The former is larger than that in 'B' and has no lateral linking as a result of greater current action in the interstructure spaces, and a more rapid upward growth. Larger Cryptozoon structures with a basal radius approaching 10 cm are also developed. Only portions of the structure are seen in borehole cores, while recrystallization has often partially obliterated the outline of the stromatolite.

iii. Oncolites : Type - SS

Oncolite structures are not well-developed in the Malmani Dolomite in the area under consideration, apart from a thin zone near the top of the formation. As shown in Plate IV (C), the oncolites have a circular to elliptical cross-section, surrounded by a light-coloured cement consisting of recrystallized dolomite. On close examination of these structures, although not evident in the plate due to the degree of recrystallization, a series of concentrically stacked spheroids (Mode 'C') are found. The laminae of spheroids are not perfectly oval in outline, but consist of minute close-linked hemispheroids. A formula of $\frac{\text{SS-C}}{\text{LLH-C}}$ can be determined for algal structures of this type. As shown in the plate, the oncolites show a complete lack of sorting. Some restriction on growth, caused by such factors as an excessive influx of clastic material, is considered adequate to explain the large size-range displayed by the oncolites.

.) The Significance of Oolites

As opposed to oncolites, oolites consist of perfectly oval spheroids, lacking the irregular internal hemispheroidal structure of the former. In well-preserved oolites, as is the case for oncolites, a concentric arrangement of the spheroids is generally developed although radial patterns are also found. The size of oolites in the Malmani Dolomite are, however, less than that of the oncolites. A chemical origin for carbonate oolites, requiring a solution supersaturated with respect to $CaCO_3$, is the most widely held view. The availability of a detrital nucleus and an agitated environment are also considered essential for oolite growth (Bathurst, 1967). In such an environment, precipitation around a suspended nucleus takes place until the so-formed oolite becomes large enough to fall out of suspension. The size of the oolite is thus controlled by the energy of the environment. An opposing idea, involving an organic origin was proposed by Schweigert (1964) who postulated the participation of algae in the incrustation of detritus. The presence of amorphous carbon, in Australian oolitic iron ores, prompted the above author to make a similar suggestion for the origin of oolites in the Malmani Dolomite. It can be concluded that for either origin an agitated environment is required.

A number of different types of oolites occur in the Malmani Dolomite. As shown in Plate V three varieties can be distinguished :

i. Chert oolites in chert (Plate V, A)

ii. Dolomite oolites in dolomite (Plate V, B)

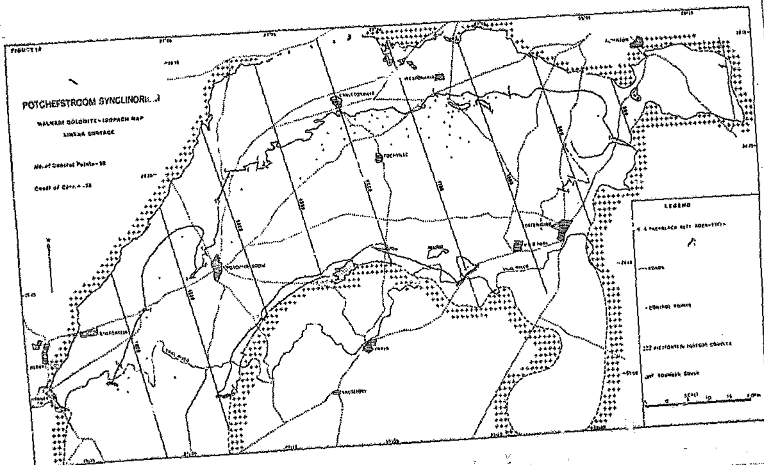
iii. Chert oolites in dolomite (Plate V, C and D)

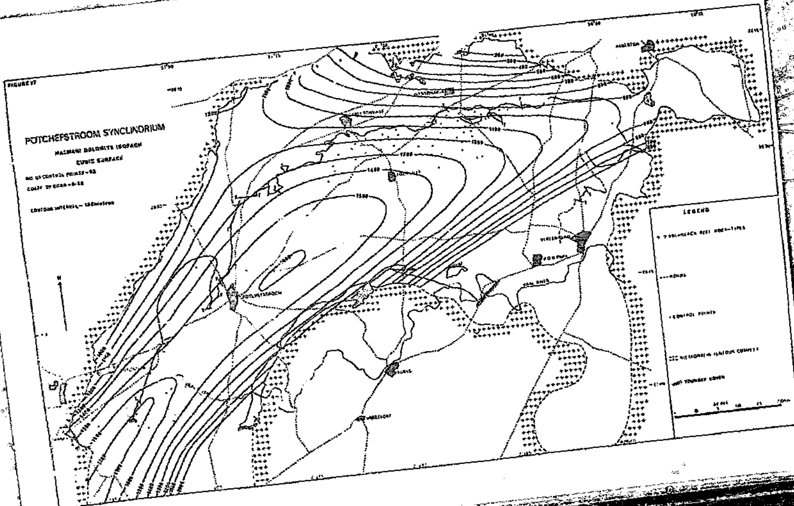
iv. Dolomite oolites in chert.

Another feature shown in this plate is that the oolites, while generally well-sorted, can also be totally unsorted. As mentioned above, the formation of oolites is directly related to energy, such that only when a critical size is reached during their formation, will deposition take place. In a stable depositional environment, a variation in oolite size, away from the shore, is thus expected, being a response to energy variations within the subtidal 'A' environment (Figure 15). Based on this argument, an unsorted oolite horizon may be formed under rapidly changing energy conditions. Oolite bands often display a distinct grading (Plate V, A). This is, however, generally of a reversed nature with larger oolites overlying smaller. An increase in energy, related to a transgressing or regressing shoreline can be inferred.

After much controversy, it is generally agreed today that oolites are indicative of pre-existing shoreline conditions. Newell and others (1960), after working on the Great Bahama Bank, concluded that conditions just below the intertidal zone are optimum for oolite growth (Figure 15). It should be noted that oncolites also form in this zone which is not an environment of high salinity in which maximum super-saturation would occur. An organic origin, proposed by Schweigert (1964) does, on these grounds, appear more acceptable than a chemical.

In the field, oolites are closely associated with domical or Collenia stromatolites either as continuous layers, or in the interdome spaces. Domical stromatolites form in a more proximal environment than oolites (Figure 15), requiring transgressive conditions for an association of the two to develop. It is thus concluded that the reversed grading of oolites is due to a transgression, as opposed to regression of the shoreline.


POTCHEFSTROOM SYNCLINORIUM
LEGEND
ROADS
CONTROL POINTS
SCALE
POTCHEFSTROOM
WESTONARIA
FOCHVILLE
CARLETONVILLE
PARYS
VEREENIGING
ALBERTON


POTCHEFSTROOM SYNCLINORIUM
MALMANI DOLOMITE ISOPACH
CUBIC SURFACE
LEGEND

The Malmani Dolomite within the Potchefstroom Synclinorium

(a) Aerial Variati n in Thickness of the Malmani Dolomite

(i) Presentation of Data

Isopach maps provide the best means of representing the aerial variation in thickness of a stratigraphic unit. Within the Potchefstroom Synclinorium, 82 boreholes penetrated the Malmani Dolomite and Fountains Formations. An additional 10 control points were obtained by superimposing structure contours of the base of the Malmani Dolomite and Timeball Hill Formations and noting the differences in elevation (at the points of intersection) of the two sets of contours. In the borehole logging, no differentiation, on a number of occasions, was made between the Malmani Dolomite and Fountains Formations. It was therefore decided that, for the purposes of the present investigation, the two formations would be treated as one unit. The maps prepared are, however, still considered as approximating to the variation in thickness of the Malmani Dolomite, the latter having a much greater thickness than the Fountains Formation. Thus, despite the fact that most of the control points lay along the northwestern limb of the synclinorium, requiring interpolation along the southeastern limb, an ideal set of data, for the construction of isopach maps, were available.

When dealing with thick stratigraphic units, it is often desirable to separate the regional from the local variations. This is necessary for two reasons :

1. Local variations are generally small-scale features which will tend to be masked within a thick stratigraphic unit. However, if separated from the regional trend and mapped alone, local thickness variations can be of grea : geological significance.

2. Conversely, the regional trend may be obscured by local variations.

A trend surface analysis was thus carried out on the unit in question, with the regional and local variations in thickness mapped separately.

(ii) Regional Variation in Thickness

To the isopach data, the linear to quartic surfaces were fitted, all of which display a remarkably high 'percentage fit'. The results of the analysis are shown in Table 4. (Page 34)

From the abovementioned table it is evident that the linear surface (Figure 16) is highly significant. This trend indicates an increase in thickness from 500 to 1200 metres towards the south-west. It is important to note that this surface bears no relationship to the present outcrop geometry of the synclinorium, indicating that the latter exerted little control on the development of the most dominant of the regional isopach trends. While not as significant as the linear, the cubic surface (Figure 17) does indicate an increase in thickness towards the axis of the synclinorium, being representative of the present geometry of the structure. The basic pattern

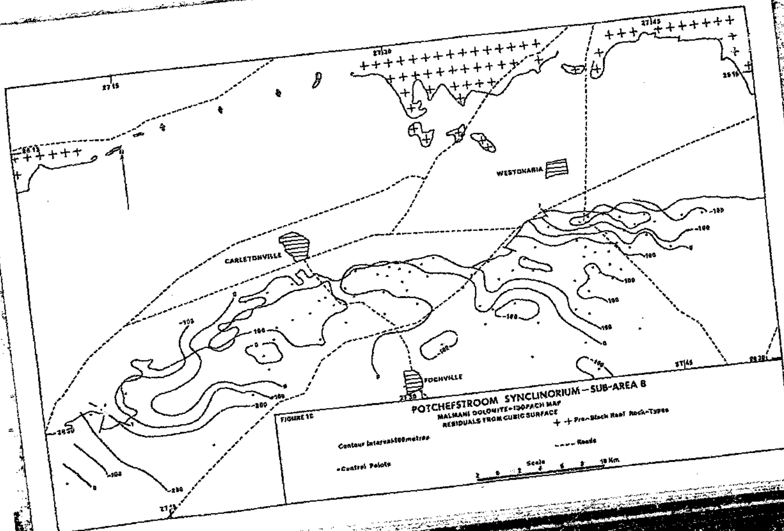


FIGURE 12
POTCHEFSTROOM SYNCLINORIUM – SUB-AREA B
MALMANI DOLOMITE-ISOPACH MAP
RESIDUALS FROM CUBIC SURFACE

of an increase in thickness to the south-west can, however, still be recognized. Figura 17 has been presented as being a better representation of the variation in thickness of the Malmani Dolomite within the synclinorium than the preceding figure. A significant feature, apparent from Figure 17, is that the Potchefstroom Anticline did not act as a regional high during Malmani Dolomite times. Although control points on and in the vicinity of this anticline are few in number, residual values do not indicate that this structure was at all active during the development of the Malmani Dolomite.

TABLE 4

Order of Surface	Coefficient of Correlation	Percentage Variation Explained by Surface	Increase in Percentage Variation Explained by Surface
Linear	0.78	60.2	
Quadratic	0.83	68.3	8.1
Cubic	0.88	77.4	9.1
Quartic	0.89	79.6	2.2

(iii) Local Variations in Thickness

As is the case with any set of data displaying a wide variation, the reliability of a compilation of this data increases in proportion to the number of control points used. For this reason it was considered that the contouring of residual values for the Malmani Dolomite should be restricted to sub-area B (Figure 6). In other parts of the synclinorium, control points were too widely scattered for a residual plot to be at all meaningful. The cubic residuals for sub-area B have been extracted from those of the total area, the contoured result of which is shown in Figure 18. This figure was found to be almost identical to that obtained when using the quadratic residuals, the regional trend of each also being similar and parallel to the strike of the formation in sub-area B.

In Figure 18, a series of alternating isopach residual highs and lows is shown. A large positive residual indicates a thickness in excess of the calculated trend value at that point, while negative residuals represent a thinning of the stratigraphic unit. Figure 18 is distinctly similar in outline to the structure contour residual plot for sub-area B (Figure 10), suggesting some relationship between thickness and structure. Along the Turffontein and Vereeniging Anticlines, which are the major structural highs in this area, minimum thicknesses are developed. The Malmani Dolomite also thins along the lower-order structural high to the east of Carletonville. Closely related to both the transverse and longitudinal downwarps, a thickening of the unit is found. This is particularly noticeable to the south of Carletonville where, at the intersection of two synclines (Figure 11) surrounded by structural highs, an elongate basin is developed in which a marked thickening of the unit occurs.

(b) Stratigraphy of the Malmani Dolomite

(i) Introduction

The stratigraphy of the Malmani Dolomite has been investigated by Young (1933) and Toens (1966). The observations of the former author were confined exclusively to the north-west Cape, apart from examining two incomplete Malmani Dolomite sections from the West Witwatersrand area. He was able to recognize a stratigraphy in the core available which, however, included less than half the total thickness of the formation in that area. Toens (1966) presented an idealized stratigraphic column for the Malmani Dolomite in the Potchefstroom Synclinorium, after examining a complete section of core from West Driefontein and two incomplete sections from the Klerksdorp area.

Both the above authors based their findings on the associations of macroscopically observable parameters. In the present study, it was decided to follow this approach further and, with the inclusion of chemical data, to attempt to define the stratigraphy of the Malmani Dolomite more precisely. As mentioned before, the use of microscopic observations as environmental indicators is largely worthless within the Malmani Dolomite, due to the high degree of recrystallization.

(ii) The Black Reef Member

The Black Reef Member, developed at the base of the Malmani Dolomite, consists predominantly of clastic material. Within the limits of the Potchefstroom Synclinorium, thicknesses in excess of 20 metres are rare, while in certain localities a thin carbonaceous shale parting is the only representative of this unit. In its most typical development, the Black Reef Member consists predominantly of quartzites, with occasional conglomerate horizons, particularly towards the base, grading upwards into carbonaceous shale-rich zones. Frequently, a quartzite horizon is present above the shales, although the first occurrence of dolomite may be found below the upper quartzite. Independent of the underlying geology, the pebbles of the conglomerates consist of well-rounded quartz, with pebbles of chert and quartzite being more rare, and with those of shale and lava present only locally. The constituents of the quartzite horizons are often rounded and well-sorted, indicative of reworking in the depositional environment. Poorly-sorted quartzites are, particularly on the flanks of the Johannesburg and Vredefort Domes, very common. In these areas, the Black Reef constituents, although consisting of well-rounded quartz grains display a large size-range, occurring within a shaly and chloritic matrix. The latter mineral is also common in the matrix of the conglomerates accounting, along with pyrite, for the dark colour often attained by the Black Reef Member.

The Black Reef Member generally has a transitional contact with the overlying 'dolomites', such that an exact boundary is difficult to define. In the preparation of isolith maps an arbitrary upper limit to the member was taken at the top of the uppermost quartzite. Where, as is the case for older boreholes, quartzites were not distinguished from shales, the thickness indicated in the log for the 'series', was used. While appreciating possible

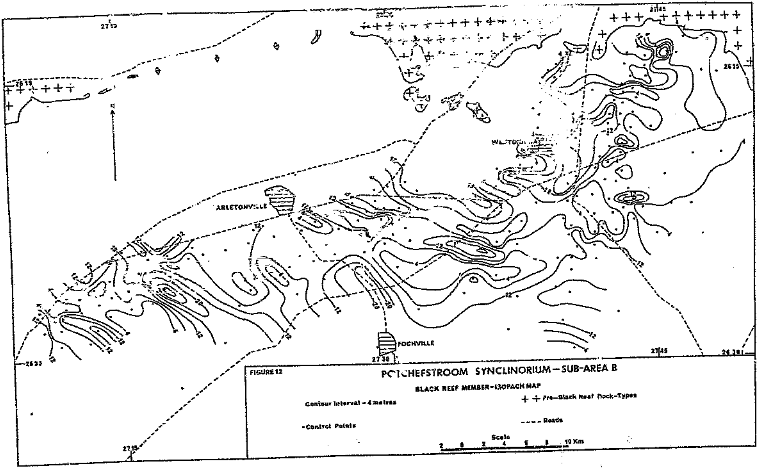


FIGURE 12

POTCHEFSTROOM SYNCLINORIUM – SUB-AREA B

BLACK REEF MEMBER–ISOPACH MAP

Contour Interval – 4 metres

+ + Pre–Black Reef Rock–Types

•Control Points

- - - - Roads

Scale

2 0 2 4 6 8 10 Km

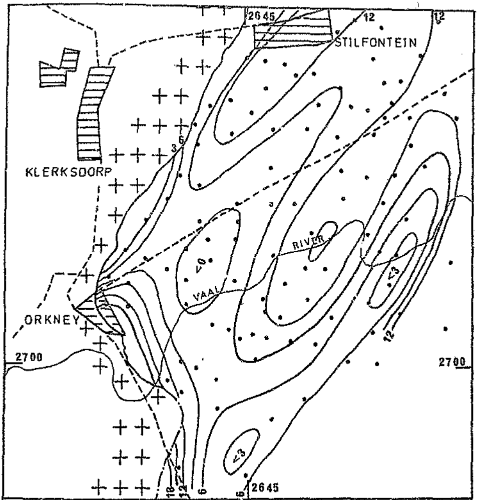


Figure 13

POTCHEFSTROOM SYNCLINORIUM

Sub-area A

Black Reef Member Thickness - Quintic Surface

No. of Control Points - 107

Coeff. of Corr. - ·45

Contour Interval - 3 metres

+ Pre-Black Reef Rock-Types

- - - Roads

• Control Points

Scale

1 0 1 2 Km

N

errors in these values, the thickness shown on the log was considered to be representative of the general order of magnitude of the Black Reef Member. Where detailed logs were available, the thickness of dolomite present below the uppermost quartzite was subtracted, such that the values used in the preparation of the maps are essentially clastic thicknesses. The maps prepared using this data can thus be termed 'Clastic Isolith Maps' for the base of the Malmani Dolomite Formation. Only in those areas with good control were isolith maps prepared. This was considered necessary, as the member has an extremely irregular distribution similar to that described in the East Rand by Papenfus (1964). For this reason, the sub-areas A and B (Figure 6) were selected for separate analysis.

Hand-contouring of untreated data was first carried out for sub-area B, the result of which is shown in Figure 12. An elongate channel pattern sub-parallel to the transverse fold trend is revealed, particularly in the Carletonville district. In the vicinity of Westonaria, a north-easterly trending pattern is more noticeable, being parallel to the longitudinal folding in this area. It is apparent, when comparing Figures 10 and 12, that the fold pattern has exerted a major control on Black Reef deposition.

In the Klerksdorp district (sub-area A), a completely contrasting geometry to that described above is developed. On hand-contouring, the data are found to have random distribution, with little resemblance to a channel geometry. There is, however, evidence of thickening and thinning of the member parallel to the structural trend in this area (Figure 9). A trend surface analysis was then carried out on the data in an attempt to relate the thickness to the underlying structure. The linear to quintic surfaces, with accompanying residuals, were determined, none of which showed very high coefficients of correlation. A correlation value of .45 for the quintic surface was, as expected, the highest. This value is considered to be significant in view of the noisy nature of the data being analyzed. A remarkably similar pattern to that obtained from the structure residuals (Figure 9) is shown by the quintic surface (Figure 13). Maximum thickness values in excess of 12 and 15 metres coincide with the longitudinal structural highs to the east of Klerksdorp and Buffelsfontein respectively, while minimum thicknesses lie along the longitudinal synclinal axis through Stilfontein. The above pattern, at first glance, seems most unusual. However, growing anticlinal structures, as will be discussed later, often have elongate sandstone bodies parallel to their axes.

Depositional Environment

The general lithological characteristics of the Black Reef Member indicate that mixed sediments were introduced into the basin of deposition. Subsequently, a certain, although variable, amount of reworking or winnowing took place. With the limited amount of introduction of mixed allochthonous sediments, a basal clastic unit, often clean in character, consisting of conglomerates and quartzites and grading upwards into shales, was developed. A later introduction of quartzitic material, controlled by mild tectonics in the source area, accounted for the upper quartzite horizon, which is often present.

As shown in Figure 12, the Black Reef Member occupies a series of river channels in the Carletonville area. For the development of such a fluvial pattern, with channelling into older sediments, a gradient was required. To account for the fine-grained assemblage overlying a coarse-grained sequence, a transgression of the shore-line must have taken place. Shaw (1964, p. 37-38) related the development of a basal clastic unit to a transgressing or expanding sea. With transgression, the above author considered that streams which were previously downcutting would have began to drop their load, due to a loss of gradient caused by flooding of their lower reaches. Such dumping would have choked the channels, resulting in braiding of the rivers, eventually forcing overloaded braided streams to deposit sands over the formerly eroding surface. As transgression proceeded, the locale of basal conglomerate and sand deposition would have moved further upstream, the lower flooded reaches receiving only the finer fractions. For those boreholes in which only carbonaceous shale was recorded at the base of the Malmani Dolomite, an interfluve locality can be inferred, over which no coarse clastics were washed, but which did experience recurring swamp-like conditions. Through the processes discussed, a diachronous basal clastic unit would have been developed. Under the above conditions, an estuarine environment would have formed. The ubiquitous small-scale cross-bedding in the Black Reef along the northern flank of the Potchefstroom Synclinorium are, according to C.E.B. Conybeare (1971, personal communication), characteristic of this type of environment. Such structures are considered to form as a result of scour and fill processes, typical of braided channels.

In the Klerksdorp area (Figure 13), the Black Reef has a completely different geometry to that shown in Figure 12. An offshore bar configuration is developed in the former area, closely resembling the stillstand sands discussed by Krumbein and Sloss (1963, p. 552). These bodies were considered by the above authors to form on growing anticlinal structures contemporaneous with deposition. Further reworking, by ocean currents, of the channel-filling basal clastic deposits could have led to the formation of such deposits. The hand-contoured map of the Black Reef Member in the Klerksdorp area did in fact reveal an indistinct channel geometry.

(iii) Logging of Macroscopic Parameters

Methods of Approach

In the Potchefstoom Synclinorium, outcrops of the Malmani Dolomite are extremely poor. Borehole cores are thus the only available sources of stratigraphic information in this area. However, particularly for a succession of rock-types such as the Malmani Dolomite, limitations exist to the construction of stratigraphic columns from borehole cores. The recognition of large stromatolites, whether of the domical or columnar type, was exthe construction of stratigraphic columns from borehole cores. The stromarecognition of large stromatolites, whether of the domical or columnar type, of sucwas extremely difficult, while the lateral extent of individual oolite or mud crstromatolite horizons was impossible to determine. Also, the recognition advantages to using borehole cores. Complete stratigraphic sections which may not always be present in the field are available, with a more regular sampling of a stratigraphic section made possible.

A number of borehole cores, of the UD series, which include the Malmani Dolomite have been preserved. Five complete sections of this formation, in the Western Deep Levels area, have been logged. Additional cores from the boreholes K4, south of the Elsburg Gold Mine, WRT1, west of Alberton, and PM2, west of Potchefstroom, were also made available to the author. The positions of these boreholes is shown in Figure 20.

21.

Initially, logging of the cores was carried out on a qualitative or descriptive basis. This proved to be a rather unrewarding effort, on account of the complex nature of the stratigraphy. A quantitative approach was then embarked on involving the recognition of six macroscopic parameters. The nature of these parameters, which are carbonaceous shales, domical and columnar stromatolites, oolites, dark finely-bedded to massive dolomite and chert, have, apart from the latter, already been discussed. During logging the degree of recrystallization of the dolomite was also noted. In each 1.50 to 2 metre core-length, the total thickness of each of the parameters was recorded. This was followed by the calculation of the percentages of each parameter in the individual core-trays, which were then plotted in the form of bar diagrams. Using this approach, it was possible to observe the vertical variation of the parameters, in different boreholes, as well as determining the association of different parameters, thus enabling different stratigraphic zones to be recognized. The above core-logging techniques was applied to five boreholes in all, namely UD 11, UD 13, UD 15, K4, and WRT 1. At this stage it was possible to relate the earlier quantitative logging to the stratigraphic zones outlined in the bar diagrams.

Having thus plotted the results from the above five boreholes individually, it was possible to recognize the same stratigraphy in each, including a well-developed marker zone in the top third of the column. While correlation could be carried out between boreholes, the thicknesses of the zones were found to differ. This variation in thickness was, however, of a systematic nature, apart from one zone mid-way up the stratigraphic column. Although over 100 metres in thickness in two boreholes, this zone was completely absent in another. It was thus decided to neglect this zone for the purposes of correlation. Having subtracted the thickness of the variable zone (v - Figure 19), the stratigraphic interval from the base of the Malmani Dolomite to the top of a prominent marker zone was found to be equal in thickness in Boreholes UD 11, 12, and 15, as well as in WRT 1 and K 4, although being 170 metres thinner in the case of the latter two boreholes. This interval was then divided into fifty equal units, and the percentages of the six parameters in each unit calculated. The average percentage of each of the parameters in the fifty subdivisions for boreholes UD 11, 12, and 15, on the one hand, and WRT 1 and K 4, on the other, were then determined. This involved the preparation of two composite stratigraphic columns from five individual boreholes, which had a smoothing effect on the vertical variation of the parameters. In the interval above the marker zone to the base of the Fountains Formation, no well-defined stratigraphy could be recognized. In the most complete stratigraphic section of the Malmani Dolomite, developed in Borehole K4, the vertical variation in parameters within this interval has been determined.

To the north of the Hartbeesfontein Anticline, particularly northwest of Krugersdorp, outcrops of the Malmani Dolomite are numerous. In this area, similar stratigraphic zones to those developed within the Potchefstroom Synclinorium can be recognized. It was thus possible to obtain a true three-dimensional picture of those zones with good outcrop, allowing for a better insight into the stratigraphy of the Malmani Dolomite.

The vertical variations of the six macroscopic parameters (Appendix II) have been plotted in Figure 19. From 0-350 metres, the results obtained from the upper parts of Borehole K4 are shown, while from 350-1210 metres the mean percentages, calculated from the individual logs of Boreholes UD 11,

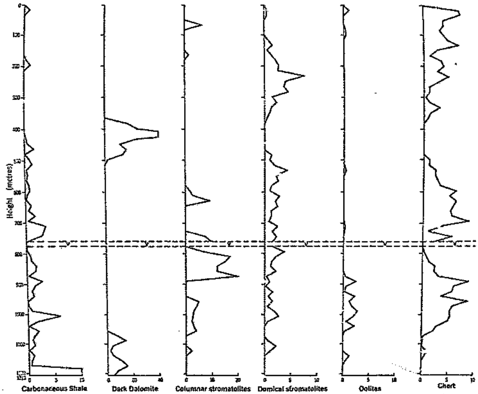


Figure 19. MACROSCOPIC PARAMETERS – Vertical Distribution

H.W.H.

12, and 15, are presented. A short discussion of the more relevant features of Figure 19, as exhibited by the different parameters, is given below. In Figure 19, the zone of variable thickness which, as discussed previously, has been subtracted from the stratigraphic column, is denoted 'v', and given an arbitrary thickness of 50 metres. The possible significance of this zone will be discussed at a later stage.

Carbonaceous Shale

In broad terms, a decrease in carbonaceous shale content with height is evident in Figure 19. The major development of this rock-type always occurs at the base of the Malmani Dolomite, at times constituting greater than thirty percent of the first sub-division, which includes the Black Reef Member. Above 400 metres, the development of carbonaceous shale in the formation is extremely limited, consisting largely of black partings which are seldom greater than 5 mm in thickness. Two secondary concentrations were present at depths of 700-760 and 1020 metres respectively, in each of the boreholes logged. Although not shown in Figure 19, occasional non-carbonaceous shale horizons are found. These are, however, of extremely limited occurrence, not having been noted in all boreholes, and confined to the stratigraphic interval between 550 and 750 metres, where developed.

Dark Dolomite

This parameter (Plate I, B), by definition, is a dark-coloured dolomite displaying little or no recrystallization. The dark dolomite occurs in two well-defined zones between 350 and 520 and 1040 and 1200 metres, respectively and which have been recognized in each borehole core investigated. The top of the upper of the two zones has been adopted as a reference plane, below which the subdivision into fifty equal intervals was made.

Columnar Stromatolites

A somewhat irregular distribution of these structures (Plate IV) is revealed in Figure 19. There are essentially two types of columnar stromatolites represented in this figure, varying in size and degree of preservation. Within the Malmani Dolomite, the maximum development and best degree of preservation of these stromatolites occurs in a distinctive zone between 770 and 900 metres. Examples of the type of stromatolites developed in this zone are shown in Plate IV. Other columnar stromatolite occurrences, shown in Figure 19, are of the larger size discussed before, and are often partly obscured by recrystallization of the host dolomite. It is noticeable that, apart from two zones, no columnar stromatolites are developed in the upper 600 metres of the formation. Horizons within the above zones are seldom greater than 50 cm in thickness, being composed of single large columnar structures.

Domical Stromatolites

The logging of domical stromatolites (Plates II and III) was somewhat hampered by the limited lateral dimensions of borehole cores. The graph presented in Figure 19 is thus representative of only the algal laminated sediments and domical structures less than 5 cm in size. The latter have, however, from field studies, been found to exist as minor parasitic domes on larger structures. The graph is thus considered to represent the occurrence of domical stromatolites, although percentages shown are probably less than are actually present. The most important feature to note on this graph is the marked persistence of this parameter throughout the Malmani Dolomite, apart from a 80-metre zone at the base and from a depth of 350 to 450 metres within the formation. There is also a noticeable scarcity of domical-shaped algal stromatolites above the latter zone.

Oolites

The abundant development of oolites within the Malmani Dolomite is confined to a zone between 860 and 1060 metres. Within this zone numerous well-sorted oolite horizons were developed in each of the borehole cores examined, varying from 5 cm to 1 metre in thickness. Other minor occurrences of oolites are present throughout the stratigraphic column but, apart from zones near the base and within the upper 100 metres of the formation, no horizons in excess of 5 cm are present. Many of the brecciated chert fragments in the overlying Fountains Formation contain oolites.

(iv) The Occurrence of Chert within the Malmani Dolomite

Distribution

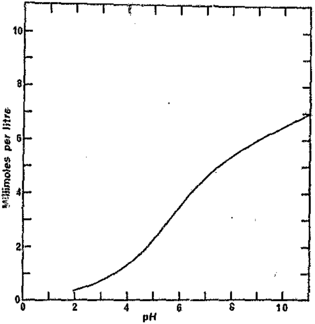
As shown in Figure 19, the occurrence of chert within the Malmani Dolomite follows a cyclical pattern. At the top of the formation an abundance of chert is found, decreasing gradually until being completely absent at a depth of 400 metres. From 400 to 700 metres there is a gradual increase in the chert content, reaching a second maximum value at the latter depth. After a sharp decrease in content towards the zone 'v', a rapid increase in the abundance of chert, to a depth of 950 metres, takes place, followed by a further sudden decrease, the rock-type being completely absent below 1,150 metres.

Mode of Occurrence and Nature of Chert

In borehole cores the chert varies in character from massive bands, up to 30 cm in thickness, down to thin stringers. At times free chert is not visible, but the highly vitreous lustre frequently assumed by the dolomite is indicative of a high silica content. During borehole logging it was not possible to record the latter form of chert, but an attempt was made to sum all other forms of this rock-type in each core length. In the field, as noticed by Toens (1966) in the north-west Cape, chert may grade into adjoining carbonate rocks or occur in well-defined beds with sharp contacts against the latter. Even within the more massive chert horizons carbonate fragments are frequently found. Ripple marks (Plate VI) are commonly found in the field, always occurring in chert and frequently displaying interference structures. Oolites and domical stromatolites are generally closely associated with the ripple marks. A noticeable relationship in borehole cores, although not possible to record quantitatively, is that between an increase in the abundance of chert and an increase in the degree of recrystallization of the enclosing dolomite.

Origin of Chert

The controversy regarding the origin of chert centres essentially around the primary or secondary nature of the rock-type and the source,



SOLUBILITY OF SILICA AS A FUNCTION OF pH (after Mason, 1962)

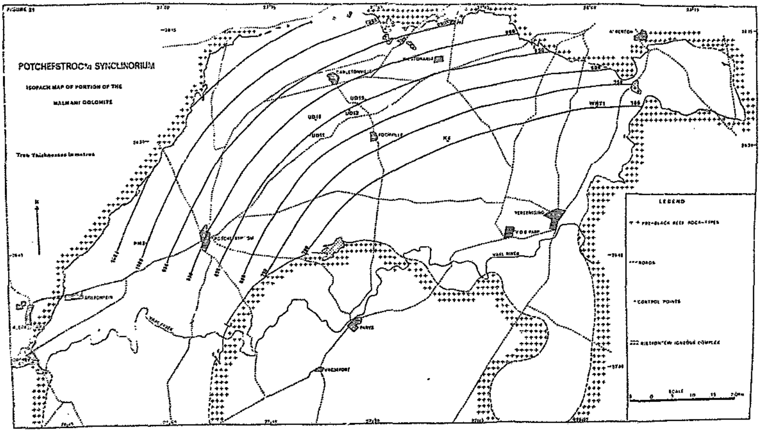
Figure 20

transport, and precipitation of silica. In the absence of volcanic activity during Malmani Dolomite times, it must be assumed that silica was derived through the normal processes of weathering and transported in solution into the depository. According to Chilingar (1956), most of the silica in sea waters is in the monomolecular form (H_2SiO_3) and, contrary to the ideas of Twenhofel (1950, p. 405), only minor amounts are present as colloidal silicic acid. Chilingar (1953) indicated that silica can be transported as a hydrophilic-colloid which he found was not very sensitive to electrolytes and could be additionally stabilized by protective colloids of organic origin.

The precipitation of chert, whether it be primary or secondary in origin, is controlled by the concentration of silica in solution and the pH of the environment. Siever (1962) pointed out that silica would not precipitate from normal sea water, indicating that with a silica content of 1 - 4 ppm, the water would have to be reduced in volume over 100 times before saturation with respect to amorphous silica could be achieved. The pH of the environment is as important as the concentration of silica (Chilingar, 1956) in controlling the precipitation of the latter. As shown in Figure 20 (after Mason, 1966) there exists an almost direct relationship between the solubility of silica and pH, precipitation being favoured under lower pH conditions. In a high temperature environment, and particularly so where evaporation is taking place, highly alkaline conditions will exist (Chilingar, 1956). Under such conditions the formation of dolomitic limestones will be favoured but the precipitation of silica will not take place. For these reasons, Chilingar (1953) anticipated that chert would increase with depth or distance from the shore, as pH conditions tend more towards neutral.

Opposed to the wholly inorganic precipitation of silica discussed above, a biogenous origin for chert has been proposed. Siever (1962), in a study of siliceous sediments in the Gulf of California, concluded that much of the chert in that area was of biogenic origin. It seems doubtful, however, whether these ideas can be applied on any large-scale to primitive chert occurrences such as are present in the Malmani Dolomite. Subsequent to deposition the silica undergoes some diagenetic change. Dehydration, followed by crystallization, results in conversion of opal to chalcedonic and microcrystalline quartz (Pettijohn, 1957, p. 443). The latter form of chert, detectable as quartz in X-ray diffraction, is developed throughout the Malmani Dolomite.

Having discussed the possible modes of origin of chert, the occurrence of this rock-type in the Malmani Dolomite can be considered. Much evidence exists for a later introduction of silica, notably the presence of carbonate fragments surrounded by chert, gradational chert-carbonate relationships within individual laminae, corroded carbonate oolites, and thin irregular chert bands and veins. Also, the development of ripple marks in primary chert, even in a siliceous gel is difficult to envisage. An explanation involving later chert replacement or chertification of a re-worked detrital carbonate horizon is more acceptable. Such an epigenetic origin could also account for the other chert relationships discussed above. Having previously argued in favour of a biogenic origin for oolites, it is considered that a primary origin for chert varieties, brought about by organic secretion of silica, is possible. However, primary colloidal precipitation of chert horizons is not, for the reasons referred to above, considered likely. Also, the fact that not all stromatolites, domical or



POTCHEFSTROOM SYNCLINORIUM
ISOPACH MAP OF PORTION OF THE
MALMANI DOLOMITE
True Thicknesses in metres
LEGEND
PRE-BLACK REEF ROCK-TYPES
ROADS
CONTROL POINTS
BUSHVELD IGNEOUS COMPLEX
SCALE
CARLETONVILLE
FOCHVILLE
VEREENIGING
VAAL RIVER
PARYS
VREDEFORT
STILFONTEIN

columnar, are silicified argues against a proposal that such organisms can secrete silica in any abundance.

The secondary nature of most, if not all, chert in the Malmani Dolomite thus seems probable. The time at which chertification takes place, however, is a matter of much controversy, hinging essentially around a post-consolidation or penecontemporaneous replacement of carbonate by chert. To the present author, the latter origin appears more acceptable, particularly so in a thick carbonate succession such as the Malmani Dolomite. A post-consolidation origin would require an enormous residual concentration of silica in solution and the maintaining of highly alkaline conditions throughout Malmani Dolomite times.

(v) True Thickness of the Malmani Dolomite

Having defined a reference plane, within the Malmani Dolomite, at the top of the upper dark dolomite zone (Figure 10), it was possible, in each of the seven boreholes, to determine the thickness of the stratigraphic interval between the base of the formation and this plane. The positions of these boreholes, together with the thickness of the defined stratigraphic interval at each point, are shown in Figure 21. Although, due to the limited number of control points available, it is not possible to accurately represent the variation in thickness of this interval, Figure 21 does show, in general, an increase in thickness to the north-west. There is also a suggestion of a bending of the isopachs around a central hub south of Parys. The above picture is in complete contrast to the result shown in Figure 17, which, along the north-western limb of the synclinorium, indicates a thickening of the total Malmani Dolomite to the south-east.

The danger of using total thicknesses of stratigraphic units in the construction of isopach maps, without defining any marker or key horizons within the interval, can be appreciated by comparing the results shown in Figures 17 and 21. The fact that the upper boundary of the Malmani Dolomite is defined by a major unconformity implies that the values used in the preparation of Figure 17 are apparent instead of true thicknesses. The apparent thicknesses are inversely proportional to the degree of uplift at any particular locality. The thinning of the Malmani Dolomite away from a central axis, with a closure in the East Rand, in Figure 17, suggests that the Potchefstroom Synclinorium was a 'struc[illegible] entity in its own right' (Brock, 1961) during the time of accumulati[illegible] this formation. These results, as discussed above, are based on appa[illegible] thicknesses. Once true thicknesses are considered, however, the axis of deposition of the Transvaal Sequence during Malmani Dolomite times must be positioned much further north with the southern edge of the basin having been situated south of the Vredefort Dome. The present variation in total thickness of the above formation is due to post-depositional uplift along the Hartbeesfontein Anticline, Johannesburg Dome and Marievale Anticline.

The above conclusions are in accord with the findings of Button (1968). Working in the Irene-Delmas-Devon area, he concluded, after constructing isopach maps, that the Johannesburg Dome was not positive during the accumulation of the Malmani Dolomite. His results also indicated that the regional palaeoslope in that area was towards the north during these times. The regional strike of the isopachs prepared by Button (1968) was N 10° E. This strike, on extension westwards, across the present Johannesburg Dome, into the Potchefstroom Synclinorium corresponds closely

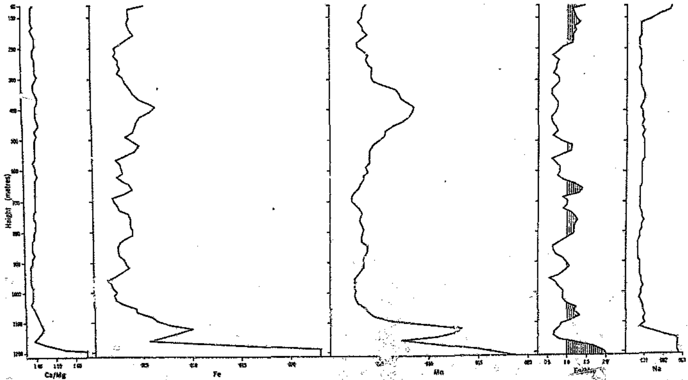


Figure 22. GEOCHEMISTRY – Vertical Distribution

with that present in the Westonaria district. On these grounds it is proposed that the two areas, namely that investigated by Button (1968) and the Potchefstroom Synclinorium, were, during Malmani Dolomite times, part of the same basin of deposition. It has not been possible to correlate actual isopachs in the two areas due to the fact that, while only a certain stratigraphic interval, representing about three-quarters of the total formation, was contoured in the area being studied by the present author, total thickness values in the Irene-Delmas-Devon area were used. The general orders of thickness of the Malmani Dolomite in the two areas are, however, similar. The great thickness of the Malmani Dolomite north-west of Rustenburg and the 'remarkable' thinning southwards towards Carolina (du Toit, 1954, p. 132) also support the above conclusions. These two areas are respectively closer towards the proposed axis and the margin of the basin of deposition of the formation, respectively.

(vi) Geochemistry of the Malmani Dolomite

Analytical Techniques

From the core of the Borehole UD 15, a total of one hundred and seventy samples were taken between the Black Reef Member and the Fountains Formation. During crushing, eighty-five composite samples, representative of a sampling grid of between 13 and 17 metres, were prepared for chemical analysis. Before crushing all visible chert was removed from the samples. The analytical techniques used on the samples involved an initial separation of the acid-soluble from the insoluble residue fraction by dissolving the crushed samples in hydrochloric acid. After preparing solutions of different concentration, those cations present in the dissolved state were detected.

In the present investigation only the major cations, namely Ca, Mg, Fe, and Mn, as well as Na, despite the low concentration of the latter, were considered relevant, the results of which appear in Appendix III. Atomic absorbtion techniques, as outlined by Lockyear (1964), appeared in theory to be the most suitable method available for the determination of the elements in question. However, while the concentrations of Fe, Mn, and Na could be detected with a high degree of confidence, the concentrations of Ca and Mg in solution were such that the large dilution factors required led to inaccurate results being obtained. It was ultimately decided that wet chemical methods offered the most reliable solution to the problem. The National Institute for Metallurgy kindly agreed to carry out the analyses of Ca and Mg, using this method.

Presentation of Results

Calcium and Magnesium

Due to a random variation of the insoluble residue content of the samples analysed, the major soluble constituents, namely calcium and magnesium, display a sympathetic random distribution. For this reason, it was decided to plot Ca/Mg ratios instead of considering the contents of the two metals separately. These ratios have been plotted in Figure 22 and show a remarkably constant trend. From the top of the Malmani Dolomite to approximately fifty metres above the base, the variation of the Ca/Mg ratios is confined to the range between 1.38 and 1.43. Below 1150 metres a sharp increase in the calcium content of the dolomite occurs, increasing the ratio to 3.5 at the base of the formation.

Iron and Manganese

The concentrations of iron and manganese in the Malmani Dolomite are universally low, such that variations in the insoluble residue content of individual samples should have no marked effect on the relative contents of these metals. Whereas the content of iron, as shown in Figure 22, does, at the base of the formation, exceed .02%, that of manganese is never greater than this value. A sympathetic relationship between the two metals is apparent in Figure 22, with the greatest concentrations occurring at the base and at a depth of approximately 450 metres below the top of the formation. The above are the most obvious anomalies displayed by the graphs, although other minor variations in the distribution of manganese do occur. At depths in the vicinity of 150, 700, and 1,000 metres, particularly low concentrations of manganese are present, coinciding with minimum iron contents, although not as accurately defined in the case of the former.

The sudden change in the concentration of both iron and manganese at approximately 1,150 metres is most noticeable. While below this depth, as shown in Figure 22, the Fe/Mn ratio is greater than 1, this ratio decreases with height until, at a depth of 1,125 metres, a minimum value of 0.7 is attained. Apart from the above relationship, the ratio graph presents a somewhat confusing picture, containing no systematic pattern. The only noteworthy feature is a broad zone of low-ratio values between 250 and 500 metres. These consistently low values correspond with the upper zone of concentration of iron and manganese in which preferential precipitation of the latter, relative to iron, has taken place. This is in contrast to the lower parts of the basal zone of concentration of these two metals.

Sodium

The sodium content of the Malmani Dolomite is extremely low throughout, averaging about one-fifth that of iron and manganese. The graph showing the vertical distribution of this element (Figure 22) contains two peaks, with a three-times concentration relative to the average sodium content at the top and bottom of the formation. Between these two zones of higher content of this alkali metal, a fairly uniform distribution of the element occurs throughout the stratigraphic succession.

Significance of Results

Calcium and Mangesium

The most important conclusion that can be drawn from the Ca/Mg graph is that the consistency of the ratios, apart from the lower 170 metres of the Malmani Dolomite, must indicate some condition of stability with respect to magnesium enrichment.

Pettijohn (1957, p. 418) gives the theoretical chemical composition of pure dolomite as follows :

MgO : 21.9%; CaO : 31.4%; CO_2 : 47.7%

The most convenient way of comparing analyses from the Malmani Dolomite with the above is by means of calculated ratios. On determining the Ca/Mg ratio from the above theoretical result a value of 1.40 is obtained. This ratio corresponds closely with all values calculated from the Malmani Dolomite analyses, down to a depth of 1,040 metres from the top of the formation. Below this depth, apart from one result, namely at 1,150 metres, an enrichment in calcium relative to magnesium occurs. Within this 170-metre interval two cycles of magnesium-enrichment are developed, with the formation of rock-types grading in composition from calcitic to pure dolomites. These observations are in agreement with the findings of Marschner (1968) regarding a decrease in $CaCO_3$ from the base to the top of individual cycles of carbonate deposition.

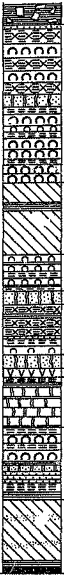
If it is considered that the constant Ca/Mg ratios are representative of complete dolomitization above 1040 metres, an explanation for the higher ratios below this depth must be forwarded. At this stage it can be concluded that either environmental changes during the deposition of the Malmani Dolomite, or porosity differences within the primary carbonate rocks are responsible for the high calcium content at the base of the formation.

Iron and Manganese

The close similarity in the distribution patterns of iron and manganese in the Malmani Dolomite suggests a close genetic relationship between the two metals. This observation is supported by the findings of Wolf and others (1967) who came to a similar conclusion for carbonate rocks of the Russian platform, although, in that area, the concentration of iron was ten times that of manganese. In discussing the genesis of siliceous or podzolic soils, Buckman and Brady (1966, p. 303) considered that acidic solutions were necessary to take iron into solution in the ferrous state, ferric iron being highly insoluble. The same authors (p. 370) noted that the behaviour of divalent manganese in solution was very similar to that of ferrous iron.

Mason (1962, p. 164) showed that the deposition of iron and manganese takes place under alkaline conditions in the ferric and tri- or quadrivalent states, respectively. For the two metals to become unstable in solution, oxidation to higher valency states is thus necessary; the energy required to oxidize iron being lower than that for manganese. Iron should, on these grounds, be deposited before manganese, the latter being stable in solution for a longer period of time, and therefore transported further. It has been noted above that suitable Eh and pH conditions are necessary for iron and manganese to be deposited. The high pH requirements are adequately met in ocean waters. According to Wolf and others (1967), who based their conclusions on over ten thousand analyses, coastal environments contain alkali conditions suitable for iron and manganese precipitation. Towards continental or lagoonal, on the one hand, and pelagic environments, on the other, the above authors found that the concentrations of these two metals decreased. A more marked basinwards decrease in concentration was noted in arid than in humid climates, and was considered to be due to the non-dilution of sea waters under arid conditions.

FIGURE 23 COMPOSITE STRATIGRAPHIC COLUMN



metres

metres	Zone
	BRECCIATED CHERT ZONE
0	CHERT-DOMICAL STROMATOLITE ZONE Chert content and degree of recrystallization of the dolomite decreases downwards. Numerous oolite bands as well as a single oncolite layer are present at the top. Domical stromatolites *occur throughout the zone, being particularly well-developed in* the lower 200 metres. Indistinct columnar stromatolites up to 25 cm in height are present in thin mottled zones.
350	UPPER DARK DOLOMITE ZONE Finely-bedded to massive dark dolomite. Carbonaceous shale bands, often greater than 1 metre in thickness, are present.
510	FINELY-BEDDED DOMICAL STROMATOLITE ZONE. Finely-bedded stromatolitic dolomite. Large and small domical stromatolites. Occasional chert and carbonaceous shale bands are present.
590	UPPER MOTTLED ZONE. Large columnar stromatolites occur in mottled dolomite.
620	RECRYSTALLIZED CHERTY ZONE. Highly recrystallized milky dolomite with an abundance of chert. Thin oolite and carbonaceous shale bands are common. Indistinct outlines of domical stromatolites are apparent.
730	LOWER MOTTLED ZONE. Large columnar stromatolites occur in mottled dolomite.
760	ZONE OF VARIABLE THICKNESS - MIXED ZONE
780	COLUMNAR STROMATOLITE ZONE. Dark to *partly recrystallized dolomite* with well-defined columnar stromatolites. Minor chert development. Domical stromatolites are rare but frequent carbonaceous shale partings are present.
890	DOMICAL STROMATOLITE-OOLITE ZONE. Finely-bedded mottled to milky dolomite. Large domical stromatolites and algal-laminated sediments occur in close association with oolites. Ripple marks are abundant. A high concentration of chert occurs. Mottled zones with indistinct *columnar stromatolites* are present.
1050	LOWER DARK DOLOMITE ZONE. Predominance of finely-bedded to massive dark dolomite but containing occasional mottled zones. *Carbonaceous shale* is abundant towards the base. Stromatolites and chert are rare.
1210	BLACK REEF MEMBER

EXPLANATION

- Dark dolomite
- Mottled Dolomite
- Recrystallized Dolomite
- Carbonaceous Shale
- Oolites
- Domical Stromatolites
- Columnar Stromatolites
- Chert

The relative iron and manganese concentrations between 1100 and 1210 and 350 and 450 metres respectively (Figure 22), are thus considered to be indicative of a coastal environment, the two zones belonging to similar depositional facies. On the other hand, the zones of low concentration of the two metals are suggestive of a facies furthest removed from the basin-edge or of an acidic swamp-like continental environment. The Eh control on iron and manganese deposition should be revealed by Fe/Mn ratios. Assuming a constant supply of iron and manganese and similar climatic conditions throughout Malmani Dolomite times, the Fe/Mn ratio should be highest in more proximal and lower in distal facies. This relationship is not readily apparent in Figure 22, apart from a decrease in the ratio from the base of the formation to 1,125 metres. Within this stratigraphic interval, a transgressing sea can, based on the above discussion, be inferred. The low Fe/Mn ratios in the upper zone of concentration of these two metals may be indicative of a slightly more distal facies, similar to that at 1,125 metres, than is present at the base of the Malmani Dolomite. Apart from the above features, no comparisons can be drawn between the iron and manganese distribution patterns and the ratio graph. No simple explanation is forthcoming for the otherwise random pattern shown by the latter graph.

Sodium

Chemical analyses show that dolomites contain variable amounts of sodium (Pettijohn, 1957, p. 418). The increase in concentration of this element at the base and top of the Malmani Dolomite, over that which is considered to be a background content throughout the rest of the formation, can be related to either primary or secondary processes. Three alternative means of concentration of sodium can be proposed, namely, evaporation, absorbtion onto clay particles, and secondary introduction of sodium along permeable zones by percolating underground waters.

(vii) Preparation of a Composite Stratigraphic Column

Using those boreholes available in the Potchefstroom Synclinorium, ten well-defined stratigraphic zones within the Malmani Dolomite have been recognized (Figure 23). While it has not been possible to subdivide the upper zone, two different associations of macroscopic parameters occur.

Lower Dark Dolomite Zone

Above the Black Reef Member, from a depth of 1050 - 1200 metres, a zone, consisting predominantly of dark dolomite (Plate I) is developed. Numerous mottled bands are present in the dark, massive to finely-bedded dolomite. Irregularities in the bedding are common throughout, but, apart from occasional small dominal and large columnar structures, the latter frequently obscured by recrystallization, no stromatolites occur. Thin, poorly sorted carbonate oolite horizons and intraformational conglomerates are common in this zone which is characterized by an almost complete absence of chert. Particularly towards the base, as the basal clastic unit is approached, a marked increase in carbonaceous shale takes place, the latter often constituting up to 30 percent of the lower 50 metres. As shown in Figure 22, this zone is characterized by the highest concentrations of calcium, iron, manganese, and sodium. There is, however, an increase in the Fe/Mn ratio towards the base, with the lower 50 metres, in particular, containing the highest iron and calcium contents.

In incomplete Malmani Dolomite sections, from boreholes south of Westonaria, Young (1933) recognized a lower stratigraphic unit similar in character and magnitude to that discussed above. He subdivided this zone into a shallow basal and deeper upper phase, having noted a decrease in carbonaceous shale content with height. Toens (1961) also described a dark-coloured basal zone, almost devoid of chert, from a borehole on West Driefontein.

Domical Stromatolite - Oolite Zone

Between 890 and 1050 metres a zone of recrystallized dolomite, varying from mottled to milky, is developed. This zone contains numerous oolitic chert bands, up to a metre in thickness, which often display reversed grading and are generally well-sorted. Although not obvious in borehole cores, field studies have revealed a close association between large domical stromatolites (Plate II) and oolites, the latter occurring in pockets between individual zones or as more persistent bands. Finely-bedded algal-laminated sediments (Plate III) are also common, while parasitic domes are often developed on the large domical stromatolites. In addition to containing numerous oolite horizons, this zone is also characterized by an abundance of chert. Chert ripple marks (Plate IV) are typical occurrences, being closely associated with oolites and often displaying interference patterns. Minor amounts of carbonaceous shale occur, being particularly concentrated towards the base of the zone. A well-defined marker horizon consisting of oolitic chert in a carbonaceous shale matrix is often present at the base. Large, poorly defined columnar stromatolites are concentrated (at 950 and 1050 metres) towards the top and bottom of the zone, respectively. Geochemical relationships within this zone are not striking apart from an antipathetic relationship between iron and manganese, as opposed to chert.

Both Young (1933) and Toens (1961) recorded rock-types similar to those discussed above, at heights of approximately 150 metres above the base of the formation. The former author noted a central 20-metres thick zone, consisting of recrystallized and laminated dolomite, which was not recognized in the present investigation.

Columnar Stromatolite Zone

The major algal stromatolite development occurs between 780 and 890 metres, constituting an easily recognizable stratigraphic zone in borehole cores. Large columnar stromatolites of different types (Plate IV, A and B) are characteristic of this zone. Domical stromatolites occur only sporadically, while chert is rare. The enclosing dolomite is generally dark and finely-bedded with frequent mottling, caused by recrystallized dolomite and carbon. The carbonaceous shale content varies from one borehole to the next, but is always less than in the two lower zones.

Toens (1961) recognized the distinctive appearance of this columnar stromatolite zone and attempted to relate his observations from the borehole on West Driefontein to those made in the Klerksdorp area. The above author reported many oolite and oncolite bands, which the present investigator did not observe, in association with the stromatolites, but showed only one such band in his stratigraphic column. The lithology of the transitional phase, between 280 and 370 metres, described by Young (1933) closely approaches that observed in this zone during the present logging.

Mixed Zone

This zone has, due to its variable thickness, been omitted from Figure 19 but should however appear in the stratigraphic column. On examination of the chert distribution in Figure 19 a decrease towards the mixed zone occurs from above and below. This observation is borne out in the individual logs in which, despite the difference in thickness for each borehole, a deficiency in chert is found. While containing minor amounts of chert, the mixed zone consists largely of finely-bedded dolomite, partially recrystallized into light and dark bands, containing numerous domical stromatolites which vary between 1 and 5 cm in size. Thin carbonaceous shale bands are common, with occasional oolitic chert zones also developed.

Mottled Zones

Two zones having a mottled appearance are developed between 590 and 620, and 730 and 760 metres, respectively. Large columnar stromatolites, frequently obscured by recrystallization, characterize these zones. Individual horizons, consisting of single stromatolite heads, are up to 50 cm in thickness. Although only part of the structure occurs in borehole cores, basal radii approaching 10 cm can be inferred for these stromatolites. In addition to the above constituents, minor amounts of chert and carbonaceous shale, as well as occasional domical stromatolites, are present.

Recrystallized Cherty Zone

Between 620 and 730 metres, a zone of highly recrystallized dolomite is developed, containing many irregular mottled horizons and with a high concentration of chert. Numerous carbonaceous shale bands, increasing in thickness towards the base are present, as well as occasional oolitic chert horizons. Domical stromatolites are sparsely developed and, where found, have poorly defined outlines, suggesting that recrystallization may have destroyed other such structures. It is also considered possible that any carbonate oolites would have been completely destroyed. Much of the chert occurs as irregular veinlets, seldom greater than 2 cm in thickness, but bands up to 30 cm in width are developed in borehole cores and in the field. The latter occurrence prompted Toens (1966) to propose a primary origin for such chert horizons. Field observations have, however, indicated that while such zones may be continuous along strike, preferential replacement, particularly of oolite horizons, has taken place, while carbonate fragments within chert are common. While Ca/Mg ratios and sodium concentrations remain constant through this zone, iron and manganese display minimum values.

Finely-bedded Domical Stromatolite Zone

Above the upper mottled dolomite occurrence, a zone of well-laminated dolomite is developed between 510 and 590 metres. The degree of recrystallization varies throughout the zone, but the dolomite never assumes a homogeneous milky appearance. Rather, alternating light- and dark-coloured laminae, representing partial and preferential recrystallization occur. Finely-bedded, algal-laminated sediments are typically developed, while domical structures up to 5 cm in size have been recorded throughout the zone. Field observations have indicated that the latter do, again, often occur as parasitic structures on larger domes. An abundant development of ripple marks was also noted. This domical stromatolite zone is characterized by a relative depletion in chert which decreases in abundance towards the top until it is completely absent in the upper 20 metres. Minor amounts of carbonaceous shale are developed, as well as occasional oolite horizons. The geochemical data display no characteristic variations within this zone. An antipathetic relationship between iron and manganese, as opposed to chert, is apparent, the two metals increasing upwards as the chert content decreases.

Upper Dark Dolomite Zone

The upper dark dolomite zone is very similar in character to that developed at the base of the Malmani Dolomite. Finely-bedded to massive dolomites occur throughout, the latter often having a dark irregularly, mottled appearance. Recrystallization is completely lacking, apart from occasional thin mottled bands. Carbonaceous shale horizons are generally less than 5 cm in thickness but, in one instance, a 2-metre thick occurrence was noted towards the top of the zone. Apart from the dark mottling, which may represent some organic growth, no stromatolites or oolites have been recorded in this zone, which is also characterized by a complete absence of chert. Veined dolomite horizons have been recorded, possibly representing infilled mud-cracks. As was found in the lower such zone, an increase in concentration of iron and manganese is associated with the upper dark dolomite occurrence. The Fe/Mn ratios are always less than 1, as opposed to greater than unity values at the base of the lower zone. It should be noted, however, that in Borehole UD 15, from which samples were taken for analysis, no carbonaceous shale was developed in the upper dark dolomite zone.

Chert-Domical Stromatolite Zone

From the base of the Fountains Formation to a depth of 350 metres, a zone consisting predominantly of chert and domical stromatolites is present. Particularly towards the base of this zone, finely-laminated dolomite, with an abundant development of domical stromatolites, occurs. Moving upwards, the chert content increases, with two maximum concentrations at 30 and 130 metres respectively, as does the degree of recrystallization. The carbonaceous shale content of this zone is characteristically low. Within this broad zone, difficult to subdivide due to gradational upward and downward increases in chert and domical stromatolite content, respectively, there are two mottled dolomite horizons. Vague outlines of large columnar stromatolites can be seen, similar to those discussed in the lower mottled zones. Towards the top of the zone, numerous oolitic horizons occur, while in the two most complete sections of the Malmani Dolomite, namely in Boreholes K 4 and PM 2, a well-defined oncolite horizon, approximately 10 cm in thickness, is present. At a depth of 200 metres, low concentrations of iron and manganese are found, followed by a marked increase, particularly in the case of the former metal, towards the top of the zone. In the upper 50 metres of the stratigraphic column, an increase in sodium takes place, reaching maximum concentrations similar to that at the base, in the upper 10 metres of the formation.

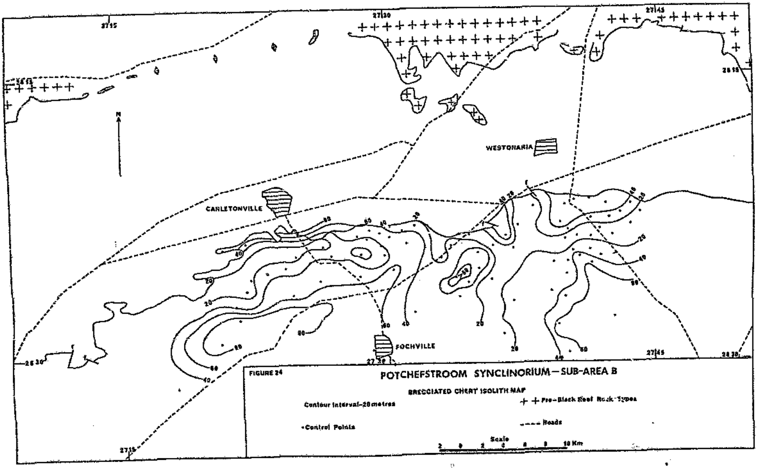


FIGURE 24

POTCHEFSTROOM SYNCLINORIUM – SUB-AREA B

BRECCIATED CHERT ISOLITH MAP

The Fountains Formation

General Lithologic Characteristics

The Fountains Formation consists of two distinct units, namely the brecciated chert zone and the Pologround Member, together constituting a single mappable unit in the field. This classification conflicts with previous ideas, including those of de Kock (1964), who placed all sediments above the brecciated chert within the 'Pretoria Series'.

(a) Brecciated Chert Zone

This zone is developed immediately above the Malmani Dolomite which it unconformably overlies, and has, on different occasions, been referred to as the 'Giant Chert' (de Kock, 1964). It is comprised of angular and sub-angular fragments of chert, with plate-like blocks, up to 1 metre in length, also common. Many fragments contain stromatolitic structures of the domical type, as well as oolites, while angular calcareous quartzite pebbles have also been noted, particularly in borehole cores. In the field, the matrix of the brecciated chert is identical in appearance to the fragmental material (Plate VII). A massive chert is developed, hence the name 'Giant Chert', often leading to some difficulty in distinguishing the matrix from the host. In contrast to the homogeneous light colour seen in the field, a dark grey to carbonaceous shale matrix is present in borehole cores (Plate VIII), enabling, at times, individual chert fragments to be fitted together.

The Pologround Member consists, in its most typical development, of quartz-chert gritty quartzites, generally well-bedded and often containing small-scale cross-bedding. Whereas the constituent quartz grains are subrounded to rounded, the chert exists as angular to subangular fragments. Frequently, and in particular to the south of Westonaria, a boulder conglomerate (Plate IX) composed of well-rounded chert boulders, up to 20 cm in diameter, in a matrix of the above quartzitic material, occurs at the base of this member. This dual-provenance rock-type has been correlated with and termed the Bevet's Conglomerate by de Kock (1964). While generally directly overlying the brecciated chert zone, a calcareous or dolomitic shale, often containing chert bands, may be developed below the Pologround Member. Shale horizons are also frequently present within this member.

Isolith Maps

(a) Brecciated Chert Isolith

Although brecciated chert zones are occasionally developed within the Malmani Dolomite, only that thickness which forms part of the Fountains Formation has been used in the preparation of the isolith map (Figure 24). In contrast to the highly variable nature of this zone found by Button (1968) in the Irene-Delmas-Devon area, a fairly regular distribution pattern is present in the Far West Rand. Only in the latter portion of the Potchefstroom Synclinorium were sufficient control points, namely eighty-five, available for the construction of isolith maps.

As shown in Figure 24, the brecciated chert zone varies in thickness from less than 20 metres to greater than 80 metres, linear belts of

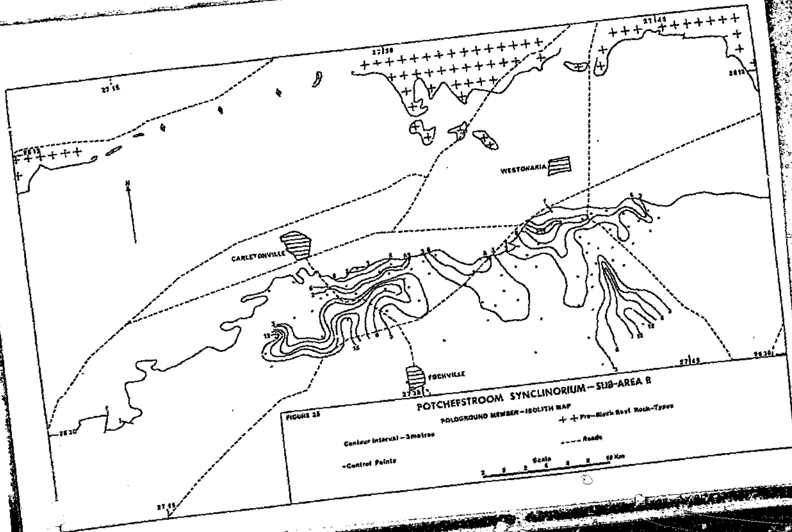


FIGURE 25
POTCHEFSTROOM SYNCLINORIUM – SUB-AREA B
FOLDGROUND MEMBER – ISOLITH MAP

maximum and minimum thicknesses being developed. The orientation of these belts is roughly parallel to the structural trends in this area, a relationship which becomes apparent on comparing Figures 10 and 24. The maximum development of the brecciated chert zone occurs on structural highs, with minimum values being present along synclinal trends. The broad isolith thickness north-west of Fochville does not lie on any obvious structural high delineated at the base of the Black Reef, but is parallel to that recognized by Knowles (1966) as being active during Ventersdorp Contact Reef times.

(b) Pologround Member Isolith

Although the lensoid character of the Pologround Member, particularly the chert conglomerate, can often be seen in the field, the subsurface mapping of this unit has been undertaken in an attempt to define its true geometry. The isolith map (Figure 25), prepared for the same area as Figure 24, outlines the channel pattern of the Pologround Member, with thicknesses from less than 3 to greater than 20 metres being developed. While the channels have a rather non-systematic distribution, a basic pattern of steep valleys and broad interfluves is evident. On the interfluves where frequently no representative of the Pologround Member is developed, the brecciated chert zone constitutes the Fountains Formation.

Origin of the Fountains Formation

There is general agreement, notably by Visser (1957) and Button (1968), that the 'Giant Chert' represents a residual insoluble product of weathering. A conflicting idea was proposed by de Kock (1964) who attributed this zone to a sheet of siliceous gel, representing the final residual precipitation product of the sea in which the Malmani Dolomite was laid down, which, on exposure to the atmosphere, dried out and cracked. The former idea is, however, in the author's opinion a more acceptable explanation in which it is considered that at the end of Malmani Dolomite times, certain areas were elevated above sea-level. Removal of the calcareous material in a subaerial environment caused slumping which was followed by infilling of the openings between the insoluble chert fragments. In tectonically positive areas which were subjected to greater uplift, maximum erosion took place, resulting in the thickest development of the 'Giant Chert'.

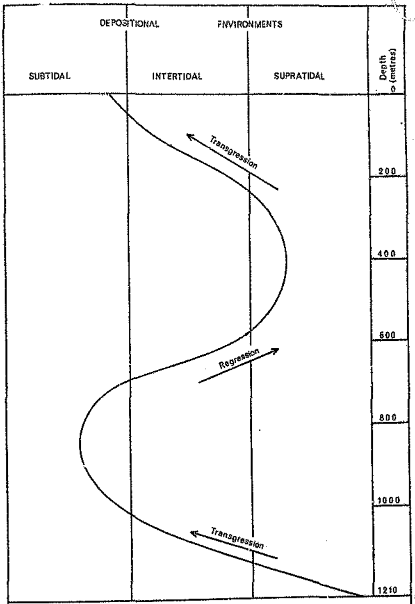
The shaley matrix of the 'Giant Chert' is also considered to represent a residual product which was squeezed into the inter-breccia spaces during slumping. Towards the top of the brecciated chert zone, the sand matrix, representing the first detrital influx of the Pretoria Group grades, where developed, upwards into thin quartzite layers, calcareous and dolomitic shales, and chert horizons which often underlie the Pologround Member. The geometry of the Pologround Member implies a fluvial deposit which has cut through the above-mentioned sedimentary horizons, and reworked the upper parts of the 'Giant Chert' into the well-rounded boulders which frequently occur at the base of this member. The matrix of the conglomerate, as well as the overlying quartzites, consist, as the relative degrees of rounding suggest, of locally derived chert fragments and of quartz grains introduced from a more distant provenance.

Environmental Reconstruction of the Malmani Dolomite and Fountains Formations

Any attempt at reconstructing the environment of formation of the Malmani Dolomite must take into consideration the constituents of the Fountains Formation. Although separated by an unconformity today, the two formations once constituted a single, largely autochthonous, depositional cycle.

The Black Reef Member, grading upwards from basal conglomerates through quartzites to shales, represents a transgressive cycle. The distance from the shoreline into the basin that the shale fraction was transported was controlled by the nature of the depository. The most *widespread of the environmental parameters, recognizable in both formations*, are domical stromatolites which are ubiquitously developed in the Fountains Formation and occur throughout the Malmani Dolomite, apart from in the two dark dolomite zones. The presence of these structures indicates a shallow-water, low-energy environment (Logan and others, 1964), such as is present in an epeiric sea. Such seas, according to Shaw (1964), p. 4) lie on the main mass of a continent and have average bottom slopes between 2 - 10 cm/km. Any allochthonous material which was being introduced into the depository would, under the prevailing low-energy conditions, have been deposited on the edge of the basin, resulting in an accumulation of argillaceous material in the supratidal environment. Grabau (1906) indicated that if, in an epeiric sea, transgression took place over a low peneplaned surface, the encroaching waters would have moved landwards over swampy ground, generating highly reducing conditions necessary for the development of black shales. This proposal is in agreement with the suggestion of Krumbein and Sloss (1963, p. 416) that euxinic conditions can develop in shallow waters as *opposed to the bathyal or abyssal* environments previously considered necessary by Rich (1951).

Above the carbonaceous shale horizons at the base of the Malmani Dolomite a thick succession of dark non-fossiliferous dolomites is present, after which the lowest zone has been named. McKee (1945) noted that in an epeiric sea, carbonate rocks lie basinwards of shales, beyond the realms of introduction of clastic material. Laporte (1967) and Shinn and others (1965) discussed the occurrence of non-fossiliferous, dark dolomites from the Manlius Formation in the U.S.A. and in the Bahamas, respectively, concluding that such dolomites develop in supratidal environments. The above authors, basing their conclusions on field observations, also favoured the idea of dolomitization being a penecontemporaneous or early diagenetic process. In Figure 15 the finely-bedded to massive dolomites of the lower stratigraphic zone will have formed basinwards of the black shales, but shorewards of the collenia stromatolites, in the upper intertidal and supratidal environments. With the *increase in energy* further away from the strand, the more proximal of the stromatolite facies, namely the collenia type structures developed in the intertidal zone. In those parts of the subtidal zone which came under the influence of wave action oncolites and oolites were formed by chemical and organic processes. Further basinwards, within the subtidal zone, contrary to the theory that all stromatolites form in intertidal environments, the energies as discussed before (p.30), are considered to have been favourable for the growth of delicate cryptozoon stromatolites.



CYCLICAL SEDIMENTATION IN THE MALMANI DOLOMITE FORMATION

Figure 25

In the above discussion, a complete transgressive sequence was developed, from supratidal braided channel deposits to a subtidal columnar stromatolite facies. From the base of the Malmani Dolomite to the top of the columnar stromatolite zone, such a sequence occurs (Figures 23 and 26), being related to a prolonged period of southward migration of the shoreline in an expanding basin. In the domical stromatolite-oolite zone, the intimate association of these two structures is indicative of numerous successive minor transgressions and regressions, in an overall transgressive phase, during the formation of this stratigraphic unit. It is considered that alternating high and low tides were responsible for such interbedded, intertidal, and subtidal, responses. During the above transgressive cycle other migrations of the shoreline must have occurred, in order to account for the minor development of columnar stromatolites within this cycle (Figure 19).

Above the columnar stromatolite zone, a reversed sequence to that already discussed is developed, representing a regressive cycle (Figure 26). This cycle culminated in the formation of a second dark dolomite zone between 350 and 510 metres below the base of the Fountains Formation. Within this zone, dark non-fossiliferous dolomites are, apart from the thick carbonaceous shale horizon present in one of the boreholes logged, the most proximal response. The recrystallized cherty zone is considered to be the intertidal-subtidal equivalent of the domical stromatolite-oolite zone of the transgressive cycle. Similarities between the two zones are the abundant development of chert and the presence of domical stromatolites, while the relative scarcity of oolites in the recrystallized cherty zone is a most noticeable difference. The possibility exists that recrystallization may have destroyed most non-chertiferous oolites. However, in a regressive sea, the development of oolites would not be favoured, suggesting that such structures never occurred in any abundance in the recrystallized cherty zone. As shown in Figure 19, a decrease in the carbonaceous shale content during the regressive, as opposed to the underlying transgressive, cycle, is found. The recrystallized cherty zone does contain amounts of carbonaceous shale. However, as suggested by Young (1934a), much of the carbon in this zone has been derived from the dolomite by some metasomatic process during recrystallization, the carbonaceous shale bands being a more advanced stage of the carbon mottling shown in Plate I (D). This relative scarcity of carbonaceous shale is in agreement with the observations of Grabau (1906) regarding the limited development of swamp-like environments in a regressive sea. Thin non-carbonaceous shale bands, recorded from the regressive sequence, also favour the presence of less reducing conditions than in the underlying transgressive succession.

From within the dark dolomite zone to the base of the Fountains Formation portion of a second transgressive cycle is present, the remainder of which has been removed by weathering or incorporated into the brecciated chert zone of the latter formation. Lithologically this zone is identical to the regressive intertidal-subtidal sequence between the upper dark dolomite and columnar stromatolite zone. Numerous oolitic chert fragments in the Fountains Formation indicate that oolites were again more abundantly developed under transgressive than regressive conditions. The only oncolite horizon recorded in the Malmani Dolomite also occurs in this zone. In addition to oolitic chert, many fragments containing domical stromatolites, as well as occasional quartzite fragments, are also present in the brecciated chert above the Malmani Dolomite. The occurrence of the latter fragments indicates that a complete depositional cycle, beginning with and culminating in the development of coarse allochthonous supratidal deposits, probably took place during Malmani Dolomite times.

While transgression is due to landward migration of the aqueous environment, regression results from shrinking of the depository, which is due to lowering of the sea-level either through evaporation or by an increase in gradient of the paleoslope. The latter, which is caused by downwarping in the depository or uplift of the surrounding terrain, is considered to be the most important process, although a combination of the two is likely, particularly in epeiric sea.

Under conditions of regression, the development of evaporites is favoured along the margins of a basin (Shaw, 1964, p. 25). In contrast, such deposits will not, according to the above author, form during transgressive cycles due to solution of any developing evaporites by the encroaching sea. Sloss (1953) discussed ways of recognizing evaporites in ancient terrains where the actual minerals have been removed in solution, and, when examining the Malmani Dolomite, he, L.L. Sloss, suggested (1970, personal communication), that brecciated chert horizons within the formation may be indicative of such deposits.

The formation of evaporites would be most pronounced in supratidal environments, more particularly along interfluves, in place of the swamp-like deposits developed during transgressive cycles. In all borehole cores examined, brecciated chert zones were not present in the Malmani Dolomite, the occurrence of such residual deposits being confined to the overlying Fountains Formation. The most proximal facies of the first regressive cycle, in the boreholes logged, is in the upper dark dolomite zone. The thick carbonaceous shale horizon which was present in one of the boreholes occurred at the top of the above zone, and is considered to be the first response of the second transgressive cycle. The intertidal-supratidal dark dolomite is thus the most proximal deposit of the regressive sequence. As shown in Figure 19, the average thickness of the Malmani Dolomite in the area being investigated is in excess of 1200 metres, indicative of a position well within the depository, to which, even during regression, the supratidal evaporite environment did not migrate. It has been noted (Figure 21) that the Malmani Dolomite thickens northwards, the shoreline thus being to the south. Examination of this formation around the Vredefort Dome revealed the presence of occasional brecciated chert zones within the Malmani Dolomite, the origin of which, it is felt, is related to slumping, possibly due to the solution of evaporites in that area. The presence of quartzites within many of the brecciated chert zones around the Vredefort Dome, has been noted, an observation which supports the above suggestion of a more proximal environment.

The zone of variable thickness or mixed zone, which occurs immediately above the columnar stromatolite zone, lies close to the boundary defining the change from transgressive to regressive sedimentation. For this reason, the possibility of a period of erosion, developed through subaerial weathering and having proceeded to varying depths in different parts of the basin, can be discounted. Also, the absence of residual chert fragments, similar to those present in the brecciated chert zone of the overlying Fountains Formation, argues against such an origin. The association of this zone with the early stages of a regressive cycle suggests some relationship between the cause of regression and the variation in thickness. The importance of uplift in bringing about regression has been discussed above, tectonic activity being most intense during the early stages of such a cycle. Irregularities, related to structural trends (Figure 11) in the floor of the depository, will thus be most pronounced at this stage. Epeiric sedimentation, it is proposed, will tend to bring about a levelling of the basin floor, thereby developing a stratigraphic unit of variable thickness on the uneven surface.

At this stage it is possible to relate the vertical variations in concentration of different metals to the depositional facies. The relative calcium enrichment at the base of the formation (Figure 22) occurs in a proximal facies, a relationship which opposes the suggestion of Chilingar (1960) that high magnesium values occur near the edge of a basin. These high Ca/Mg ratios are, however, in agreement with the findings of Marschner (1968) who noted an increase in the magnesium content of carbonate rocks with height in a sedimentary cycle. The reasons for the calcium enrichment at the base of the Malmani Dolomite are, in the author's opinion, related to climatic changes. The changes in the clay mineral assemblage, within this stratigraphic column, from kaolinitic at the base to illitic higher up, have been noted (p. 28) and were considered to imply that a humid climate, of limited duration, prevailed in early Malmani Dolomite times. Whereas under arid conditions, high magnesium values can develop in residual solutions (Deffeyes and others, 1965), this is less likely in more humid climates, resulting in less complete dolomitization of earlier-formed limestone.

Highest iron and manganese concentrations are also present in the proximal facies. In contrast to the enrichment in calcium, which was confined to the lower such facies, the enrichment in iron and manganese is present both in the basal and in the upper dark dolomite zone, necessitating an explanation other than climatic. The observations of Wolf and others (1967) can be readily applied to the occurrence of the above two metals in the Malmani Dolomite. While no analyses were undertaken from the carbonaceous shale-rich lagoonal facies, marked increases in the concentration of iron and manganese have developed in the coastal environment, decreasing basinwards. Upon introduction of these two metals in acidic solution, into the alkaline depository, immediate precipitation took place, minor amounts being transported into the basin. The decrease in the Fe/Mn ratio with height in the lower 60 metres and the consistently low ratios in the upper dark dolomite zone are in accord with the suggestions made before (p. 46) regarding a transgressive sequence and a more distal facies respectively, and the greater solubility of manganese relative to iron.

While no obvious explanation for the sodium distribution curve can be given, it is considered that the lower concentration is related to the high shale content of the basal zone, the alkali metal existing in an adsorbed state. The major unconformity at the top of the Malmani Dolomite would have enabled late percolating waters to concentrate sodium along and below this erosion surface.

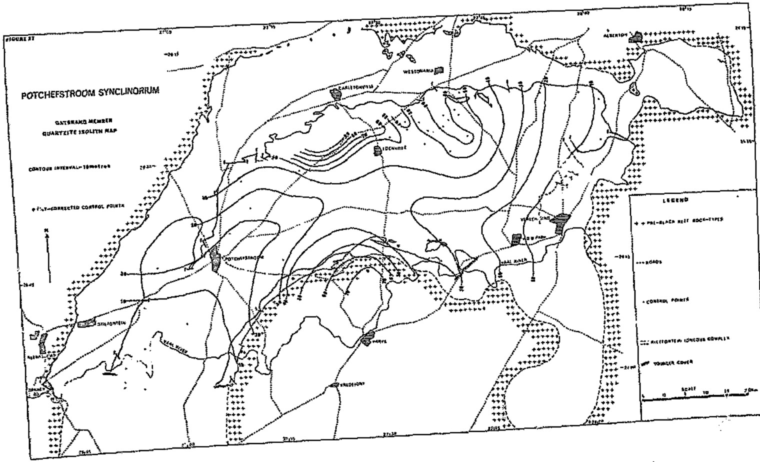
The unlikelihood of the extensive dolomite deposits present in the Transvaal Sequence having formed by primary precipitation has been discussed (p. 22). Rather, a residual enrichment of magnesium in solution would have taken place as limestone was being precipitated, maximum concentrations of the metal having developed under arid conditions in shallow water to supratidal environments, particularly where evaporation was pronounced (Deffeyes and others, 1965, and Hsu, 1966). Under such conditions, Chilingar (1953) noted that highly alkaline conditions exist, most favouring the solubility of silica (Mason, 1966). Penecontemporaneous dolomitization of earlier formed limestones, involving the replacement of calcite by dolomite, would have commenced in the supratidal environment before progressing basinwards, by the migration of the brinal solutions through more distal facies. Complete dolomitization, such as has taken place through most of the Malmani Dolomite, was dependent on the availability of magnesium in solution. If low concentrations of this metal were present in solution, dolomitization would have been confined to the more proximal facies, as a result of the equilibrium or initial Ca/Mg ratio having been rapidly attained, as the released calciu s taken into solution, or would have been incomplete.

The formation of secondary chert depended on the solubility of the carbonate host, at that stage at which silica was insoluble in solution. Chertification is considered to be closely associated with the dolomitization cycle, the same solutions being responsible for both processes. Within an evaporitic environment, the concentration of silica, considered necessary by Siever (1962), could have been achieved, but precipitation would not have been favoured under the evaporitic and alkaline conditions discussed above. In a more distal facies, where dilution resulted in a lowering of the alkalinity of the solutions, chertification would have taken place. The control of pH on chert precipitation adequately explains the occurrence of the rock type in the Malmani Dolomite. On comparing Figures 19 and 26 it is noted that in both supratidal to upper intertidal dark dolomite zones, little or no chert is present, maximum concentrations being present in the intertidal to subtidal domical stromatolite-oolite associations. Within the true subtidal columnar stromatolite zone, a relative depletion in silica occurs. This is considered to be due simply to the fact that most of the dissolved silica had been precipitated in the more proximal facies, particularly so in the highly permeable oolite zones. It was also noticeable that the thickest chert bands were present in the domical stromatolite-oolite zone. This implies that the chertification was controlled by the original carbonate facies with the thick chert horizons therefore following diachronous strata.

The Timeball Hill Formation

Introduction

The stratigraphy of the Timeball Hill Stage in the Potchefstroom Synclinorium, including the Pologround Member but not those shales above the Gatsrand Member, has been described by Nel and Jansen (1957), Nel and others (1939) and Nel and others (1935). The above authors concluded that the quartzites present, although not as interrupted by shales as in the vicinity of Pretoria, could be correlated with those in that area. Jansen (1953a, and 1953b) also discussed this stage, where developed around Vereeniging and Lindequesdrift, recognizing either one or more quartzite horizons. In the latter area, however, as has been discussed in a previous section (p. 14), a variable number of quartzite lenses are developed. Detailed stratigraphic columns of the lower parts of the above stage were prepared by Brock (1961) in the Far West Rand, using borehole information. With the aid of deeper boreholes in the same area de Kock (1964) presented four columns including the complete Timeball Hill and Daspoort Stages.


POTCHEFSTROOM SYNCLINORIUM
QUARTZITE ISOLITH MAP
LEGEND
ROADS
CONTROL POINTS
YOUNGER COVER
SCALE
POTCHEFSTROOM
CARLETONVILLE
WESTONARIA
PARYS
ALBERTON
VAAL RIVER

The Timeball Hill Stage, above the Fountains Formation, and the lower Daspoort Stage are given formational status, together constituting a single depositional cycle. The Timeball Hill Formation consists almost exclusively of allochthonous sediments, representing a response to increased tectonism, as opposed to that operative during Malmani Dolomite and lower Fountains Formation times. Considering the Timeball Hill Formation as a single unit, its variation in thickness and stratigraphy, within the Potchefstroom Synclinorium, will be discussed in an attempt to determine the depositional and post-depositional history of this formation.

General Stratigraphy

(a) The Argillaceous Sediments

The lower shales of the Timeball Hill Formation are similar in character to those present within the Fountains Formation, overlying either the Pologround Member or the brecciated chert zone, where the former is absent. Calcitic or dolomitic shales with thin chert bands, at the base of the formation, representing a transitional zone from chemical to detrital sedimentation, give way rapidly to carbonaceous and ferruginous shales further up. The latter shale types are the most abundant sediments in the Timeball Hill Formation, always constituting greater than 60 percent of the total thickness.

While the ferruginous shales have a dark red colour in borehole cores, a light or bleached appearance was noted in the field. These argillaceous sediments are generally finely-bedded, otherwise being completely structureless. Carbonaceous shales vary in abundance from one borehole to the next. While in two boreholes such shales occur throughout the formation at the expense of the ferruginous variety, they are completely absent at other localities. Most typically, the carbonaceous shales are developed immediately above and/or below the Gatsrand Member and, although always finely-bedded, do contain numerous sedimentary structures. Small-scale ripple marks are common (Plate X), while the material filling the ripples is generally light-coloured and siltose in character, often displaying minute cross-bedded laminae. The lensoid light-coloured siltose material in a dark background have been termed flaser structures by Pettijohn and Potter (1964, Plate 17), as superficially resembling such features in mylonites and other metamorphic rocks.

(b) The Gatsrand Member

The Timeball Hill Quartzite Isolith Map is shown in Figure 27. Maximum thicknesses in excess of 80 and 100 metres respectively are developed in the vicinity of the Rietfontein Igneous Complex on the south-western limb of the synclinorium, and along the Gatsrand Ridges south of Carletonville. Towards the axis of the synclinorium and to the east and south-west of the above two areas of maximum development, a thinning of quartzite occurs. Along the easternmost extent of the Timeball Hill Formation, quartzite thicknesses of less than 10 metres are found, while, in the south-western parts of the area being investigated, no quartzite horizons are developed. Along most of the north-western limb of the Potchefstroom Synclinorium, a single thick quartzite horizon (Plate XI) occurs, such that the Timeball Hill Quartzite Isolith is equivalent to the Gatsrand Isopach. To the south of Westonaria, however, two or three quartzite bands occur, all of which are greater than 10 metres in thickness.

Moving further eastwards, thin impersistent elongate lensoid bodies of quartzite are developed above a lower continuous horizon. Around the Vredefort Dome, the Gatsrand Member is similar in character to that just discussed. One or two continuous quartzite horizons, always less than 10 metres in thickness, are generally overlain as well as underlain by impersistent lenses (Plate XII). During a field traverse north of the Rietfontein Igneous Complex, eight quartzite horizons were noted, varying from 3 to 20 metres in thickness, leading to some difficulty in defining the limits of the Gatsrand Member. Further to the west, a distinct quartzite lens, having a strike-length of 10 metres and closely resembling the Pologround Member in field appearance, was noted.

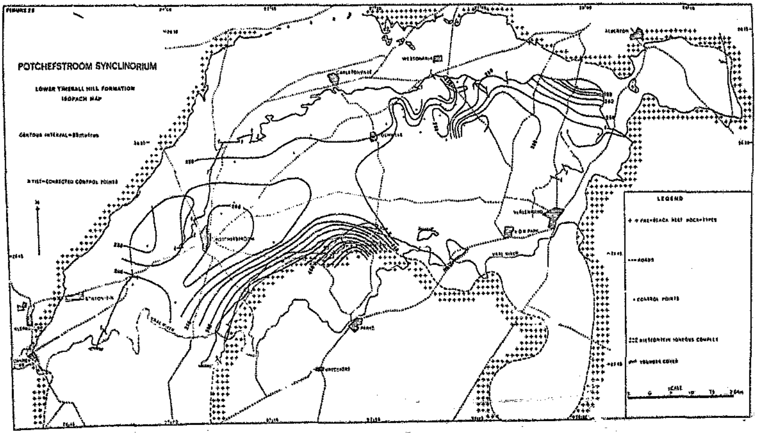
Macroscopically, the quartzites of the Gatsrand Member vary from light-green, through different shades of red, to white in colour, the former being confined to fresh samples in borehole cores. Polished section examination of the quartzites showed the red coloration to be due to hematite, resulting from oxidation of what was probably an original iron silicate cement. Further exposure to the atmosphere led to leaching away of the cement, with the quartzites assuming a bleached white appearance.

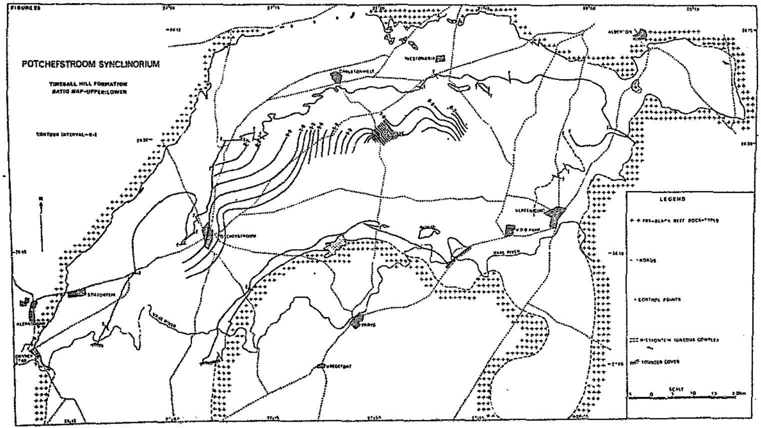
A series of 30 Gatsrand quartzite samples was taken throughout the synclinorium for microscopic examination, in an attempt to relate such parameters as grain-size, degree of rounding, sorting, and maturity to the quartzite isolith map (Figure 27). All quartzites examined were found to be highly mature, consisting of quartz grains in a ferruginous cement, with no rock fragments, felspars, or clay minerals being present. In the area of maximum quartzite development, to the south of Carletonville, poorly sorted quartzites occur, consisting of subangular to subrounded quartz grains, varying in size from .06 to .30 mm. Around the Vredefort Dome, poorly sorted quartzites are again found, with the degree of rounding of individual quartz grains also similar to that in the above area. Associated with this thinning of the quartzites to the south-west, an increase in the degree of sorting occurs. Although the degree of rounding remains similar to that in the Carletonville area, there is a marked decrease in the average grain-size. A less obvious relationship, between quartzite thickness and sorting, than that discussed above, is evident in the east. While the quartzites are still poorly sorted, an increase in the degree of rounding occurs, subrounded to rounded quartz grains predominating in all samples studied from that area.

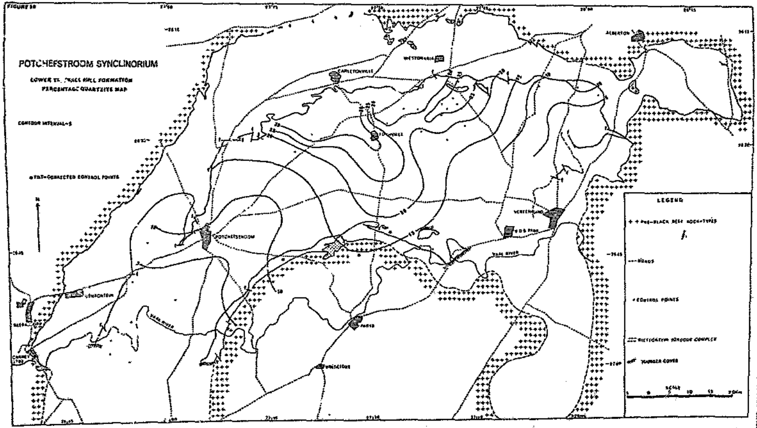
An attempt was made to determine the paleocurrent pattern operative in the Potchefstroom Synclinorium during Timeball Hill times. This, however, proved to be an extremely difficult undertaking due to the trough-like nature of all cross-bedding. While measurement of the attitudes of individual foreset beds was possible, the results, on plotting, gave a spread of 180°, such that no meaningful interpretation could be made, other than that transport of material took place from a general northerly direction.

Isopach Maps

In order to obtain some insight into the aerial variation in thickness of the Timeball Hill Formation, a number of different isopach maps were constructed. Initially, thicknesses of the lower part of this formation, termed the lower unit, from the top of the Fountains Formation


POTCHEFSTROOM SYNCLINORIUM
LOWER TIMEBALL HILL FORMATION
ISOPACH MAP
LEGEND
ROADS
SCALE


POTCHEFSTROOM SYNCLINORIUM
LEGEND
CONTROL POINTS
SCALE
0 5 10 15



POTCHEFSTROOM SYNCLINORIUM
CARLETONVILLE
WESTONARIA
ALBERTON
POTCHEFSTROOM
VEREENIGING
PARYS
VAAL RIVER
LEGEND
ROADS
CONTROL POINTS
SCALE

to the top of the Gatsrand Member, were used for the compilation of an *isopach map*, followed by the preparation of a similar map for the remainder of the Timeball Hill Formation. The contoured result of the former is presented in Figure 28. Maximum thicknesses, in excess of 300 metres, occur around the north-western arc of the Vredefort Dome and to the south-east of Westonaria. In a broad east-west belt south of Carletonville, and to the west of Potchefstroom, a thickening of this unit also occurs. Minimum thicknesses of less than 225 and 150 metres are developed south of Fochville and along the north-eastern boundary of the Pretoria Group outcrop. To the east and south of Potchefstroom, a thinning of the lower unit also takes place.

While in the eastern parts of the synclinorium a thickening towards the centre of the structure occurs, the opposite is the case in all other regions, minimum thicknesses being developed along the axis with the unit thickening to the north and south. Across the Potchefstroom Anticline, a bending of the contours is evident on Figure 28, due to a thinning of lower unit over this structural trend which was thus active during lower Timeball Hill Formation times. This map also indicates that the present structural high to the north-west at Potchefstroom was not active during lower Timeball Hill times, although it is not possible to postulate on the attitude of the Hartbeesfontein Anticline in this area.

Neither the isopach map of the remainder of the Timeball Hill Formation (upper unit) nor that for the total thickness has been presented, as a map of the ratio of the upper to the lower unit (Figure 29) was considered to be more meaningful. Although a limited number of control points, all along the north-western limb of the *synclinorium*, were used in the preparation of this map, a well-defined pattern has been obtained. From the west and east, towards Fochville, an increase in this ratio is found, indicative of a maximum development of the upper unit in the latter area, this unit being thinnest in the west and east.

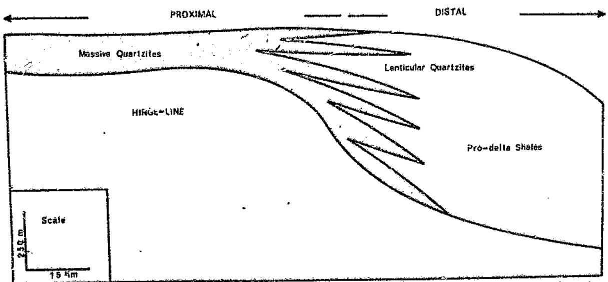
Lithofacies Mapping

Due to the nature of the data available, the only lithofacies mapping which could be undertaken was that to compare the contents of arenaceous to argillaceous sediments in the lower Timeball Hill Formation. A percentage quartzite map for this unit was prepared and is shown in Figure 30. From areas of maximum development to the south of Carletonville and Westonaria respectively, the percentage of quartzite decreases to the west, south and east until to the south of Potchefstroom and in the Vereeniging district this rock-type constitutes less than two percent of the unit.

Although it is not possible to map the aerial distribution of the relative contents of carbonaceous and ferruginous shale in the lower Timeball Hill Formation, borehole logs have indicated that the former predominates in these areas of maximum quartzite development, along the northern limb of the synclinorium. In a number of boreholes, particularly to the south of Westonaria, no ferruginous shales were reported. On the other hand, during field traverses across this unit, on the margins of the Vredefort Dome and in the Vereeniging area, as well as from boreholes to the south of Potchefstroom, no carbonaceous shales were noted.

Figure 31

THE GEOMETRY OF A DELTA



modified after Krumbein and Sloss, 1963

Depositional Environments and Lithofacies

Each of the major rock-types present in the Timeball Hill Formation, namely carbonaceous shales, mature quartzites, and finely-laminated ferruginous shales, characterise a particular environment of deposition. The interaction of these three depositional environments has resulted in the development of the lithofacies pattern shown in Figure 30, as well as determining the distribution of the two shale-types within the synclinorium.

The nature of the carbonaceous shales with associated siltose lenses suggests a shallow-water, agitated environment in which ripple marks and cross-bedding could develop. Flooded backswamp or marsh-like regions associated with major river systems were reported by Thornbury (1969, p. 169) to favour the development of such lithologic associations. Recent studies in the Gulf of Mexico (van Andel and Curray, 1960) indicated that mature, fine- to medium-grained, and generally well-sorted sands were developed in the littoral zone. Sediment which was introduced into the sea by rivers was winnowed and redistributed by waves and currents and carried out to depths of from 20 - 30 metres (Johnson, 1956). The fine-grained fraction of the river-load was transported into deeper water environments before settling slowly out of suspension to form well-laminated but otherwise structureless shales.

The distribution of the above three rock-types within the Potchefstroom Synclinorium can be related to a deltaic model, as developed by Fisk and others (1954) and Fisk (1961), after studying the geometry of the Mississippi Delta. Carbon-rich clayey silts occur in marsh-like areas exposed above sea-level in the proximal facies of the delta, grading seawards into different types of sand bodies. Finely laminated shales cover the delta-front, referred to as the pro-delta facies by Fisk and others (1954). A distinction was drawn by Fisk (1961) between 'deep-water delta sands' characterized by bar finger and lensoid sand bodies amid pro-delta clays and 'shoal-water delta complexes'. The latter are more massive in character and form where wave action and longshore currents, as discussed by Johnson (1956), affect further transport of sediments. With regression along a delta-front, the sands reworked by shore agencies may be spread as regressive 'delta-front sheet-sand bodies' (Fisk, 1961). The distances over which regression can take place has been illustrated by Swann (1964) who showed that during Mississippian-Pennsylvanian times the shoreline had shifted over 900 km through Indiana and Illinois.

The lontitudinal geometry of a delta is illustrated in Figure 31 (modified after Krumbein and Sloss, 1963, p. 542). Whereas in the proximal parts of the delta high sandstone percentages are developed, a basinward decrease in the sandstone:shale ratio occurs, associated with which is an overall thickening of the deposit. It should be noted (Figure 31) that, although the percentage of sandstone decreases away from the mouth of the river, there need not necessarily be a decrease in the total sand content. In the most distal or extreme delta-front facies of a delta, where sands are absent or only sporadically developed, a total thinning of the deltaic sediments is found.

The geometry of a major delta, introduction of sediment being from the north, is outlined in Figure 30. A decrease in percentage quartzite in the lower Timeball Hill Formation away from the north is shown.

Figures 27 and 28 also display patterns typical of deltas. In proximal environments, thick, massive quartzites of the 'shoal-water delta' type (Fisk, 1961) are developed, grading basinwards into lensoid bodies and thinner horizons of quartzite, associated with which is a total thickening of the deposit. The thinner, but continuous, quartzite horizons are probably 'delta-front sheet-sands' (Fisk, 1961), formed during regression of the shoreline. An extreme delta-front facies is developed south of Potchefstroom where a thinning of the lower Timeball Hill Formation is accompanied by a thinning and eventual complete disappearance of quartzites. The decrease, both in thickness and quartzite content, in the centre of the synclinorium is the only anomaly in the proposed deltaic model. It is, however, considered that basinwards of the hinge-line, where a shallow-water (Figure 31) proximal facies grades into deeper-water deposits, areas of non-deposition will exist as a result of a sudden increase in velocity of the transporting medium, related to the steeper gradient of the floor. The association of carbonaceous shales with thick massive quartzites in the northern part of the synclinorium and the absence of the former in the south, where laminated shales are developed instead, supports the proposal of a deltaic model of deposition.

In a deltaic deposit, as opposed to that associated with a clastic wedge, Krumbein and Sloss (1963, p. 544) have noted that highly mature quartzites will be present, as a result of reworking by waves and ocean currents. Sorting displayed by the quartzites will also be a function of the degree of reworking. In areas of maximum quartzite development in the Gatsrand Member, in the north and south of the Potchefstroom Synclinorium, largest average grain-sizes and poorest sorting are found. Associated with a wedging out of the quartzites, notably in the Potchefstroom area, the degree of sorting increases, related to which is a decrease in the average grain-size. The above observations, considered in conjunction with Figures 27 and 30, are in accord with depositional environments within and on the margins of a delta, respectively.

The Regional Setting of the Potchefstroom Synclinorium during Timeball Hill Times

Having discussed the geometry of the Timeball Hill Formation in the Potchefstroom Synclinorium, it is now necessary to fit the latter area into the framework of the total Transvaal Basin during Timeball Hill times.

The most comprehensive study, to date, on the Transvaal Sequence was undertaken by Visser (1969), who prepared a number of isopach and litho-facies maps for the Timeball Hill Formation. The same author also conducted a number of field traverses across the Pretoria Group to the north of the Johannesburg Dome. He reported a limited development of carbonaceous shales in the Timeball Hill Formation, and a complete absence of the latter where quartzite horizons were present. The latter rock-types occur at a similar stratigraphic level to those of the Gatsrand Member in the Potchefstroom Synclinorium. As many as ten separate quartzite horizons were reported in certain areas to the east and west of Pretoria, being interlayered with finely-laminated ferruginous shales. Individual quartzites were not easily traced along strike, and the fact that fewer horizons were developed at certain localities, suggested a lenticular geometry.

On a more regional scale, Visser (1969) noted a southwards decrease in the quartzite content of the Timeball Hill Formation, from over 100 metres in the Potgietersrust area to a complete absence of this rock-type in an arc through Klerksdorp, Kroonstad and Bethal. While the above pattern suggested a smooth decrease in quartzite content, away from a northerly source area, closer examination during the present study showed that this was not strictly the case. Whereas numerous thin, and often lenticular quartzites, as discussed above, occur north of the Hartbeesfontein Anticline, thick and massive quartzites are present along the Gatsrand to the south of this structure. The latter occurrence of arenaceous sediments thus lies between lenticular quartzites to the north and south, complicating the picture of a smooth decrease in quartzitic material southwards, and arguing against a single cycle of sedimentation as being responsible for the development of the Timeball Hill Formation in the main Transvaal Basin and in the Potchefstroom Synclinorium.

The Timeball Hill occurrences immediately north of the Hartbeesfontein Anticline and on the margin of the Vredefort Dome are lithologically and geometrically somewhat similar, both having the configuration of delta-front deposits, with lenticular quartzites occurring in finely-laminated pro-delta shales. It is suggested that the Timeball Hill Formation in the main Transvaal Basin and in the Potchefstroom Synclinorium belonged to different periods of sedimentation, the former having developed first with the latter having formed at a later time, after a major southwards regression of the shore-line. During the deposition of the Timeball Hill Formation in the main Transvaal Basin, the shore-line, at different times, must have regressed from north of Potgietersrust as far south as Pretoria to account for the mature nature of the quartzites north of the Johannesburg Dome. In later geological times, however, when the Timeball Hill Formation was developing in the Potchefstroom Synclinorium, a major southwards regression of the shore-line into the Carletonville area, occurred, with migrations across the synclinorium resulting in reworking of quartzites on the margins of the Vredefort Dome.

THE STRUCTURAL EVOLUTION OF THE POTCHEFSTROOM SYNCLINORIUM

It has been shown that the present-day fold pattern developed in the Potchefstroom Synclinorium (Figure 11) was initiated in pre-Witwatersrand times, being caused by epeirogenic activity within the basement. Two fold trends, namely a longitudinal and transverse, have been delineated, evidence having been cited that the former was the earliest, although renewed activity along each has taken place. During pre- and post-Black Reef times a number of pulsating tectonic elements were active, the most important of which were the Ottosdal Anticline, the Hartbeesfontein Anticline and associated Johannesburg Dome, and the Vredefort Dome. To the south-east of the latter a north-east to south-west trending basement high through Standerton and Senekal exists (Figure 2), overlain by Karroo strata (Borchers, 1961).

TABLE 5

THE STRUCTURAL EVOLUTION OF THE POTCHEFSTROOM SYNCLINORIUM

TIME OF TECTONIC ACTIVITY	OTTOSDAL ANTICLINE	JOHANNESBURG DOME	HARTBEES-FONTEIN ANTICLINE	VREDEFORT DOME	SOUTHERN BASEMENT HIGH
Late or post-Transvaal Sequence	———	X X X	X X X	X X X	X X X
	—u—	—u—	—u—	—u—	—u—
post-Timeball Hill Formation	———	X X X	X X	———	X X
During Timeball Hill Formation	———	X X	X	———	X X
Pre-Fountains Formation	———	X X	X	———	X X
During *Malmani* Dolomite Formation	—u— / —p—	—u— / —p—	—u— / —p—	—u— / —p—	—u— / —p—
During Ventersdorp Sequence	X X	X X	X X	(X) ?	X X
During Witwatersrand Sequence	X X X	———	———	X	X X

X X — Relative Degree of Tectonic Uplift

——— — Period of No Tectonic Activity

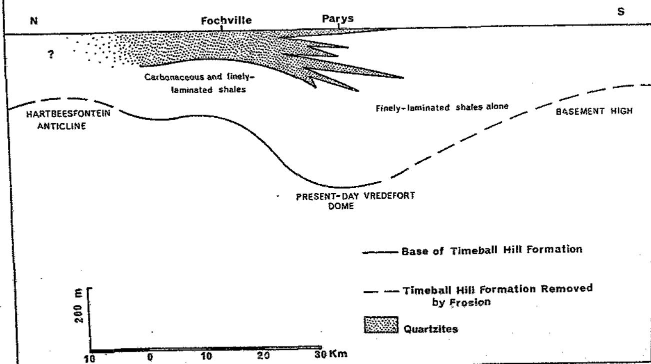
—u— — Unconformity

—p— — Partly Unconformable

As previously discussed (p. 10) and shown in Table 5, the Ottosdal Anticline was the dominant positive structural trend during Witwatersrand times. As shown by isopach maps (Brock and Pretorius, 1964a) the basement high through Standerton and Senekal defined the south-eastern edge of the basin, with the Vredefort Dome also having had some influence on the deposition of Witwatersrand *strata*. At the time of emplacement of the Ventersdorp Lavas, however, each of the structural elements was of similar magnitude. It should be noted that although, as shown in Figure 3, the lavas are considered to occupy a trough between the Ottosdal and Hartbeesfontein Anticline, no indisputable evidence is available for the existence of a similar lava-filled structure around the periphery of the Vredefort Dome, as suggested by Brock and Pretorius (1964a). At the termination of Ventersdorp Volcanism, a paleoslope to the north-west was developed, off the basement

Figure 32

NORTH-SOUTH CROSS-SECTION: LOWER TIMEBALL HILL FORMATION AT TIME OF DEPOSITION



high in the Standerton-Senekal area. The Malmani Dolomite was deposited in a uniformly shallow sea, thickening to the north-west, isopach data from the Potchefstroom Synclinorium (Figure 21) and from the Irene-Delmas-Devon area (Button, 1968) indicating that the Ottosdal and Hartbeesfontein Anticlines, as well as the Johannesburg and Vredefort Domes, were inactive during these times. Secondary structural trends, operative during Ventersdorp Contact Reef times (Knowles, 1966), were shown to have been active during the development of the Malmani Dolomite, maximum residual thickness values for this formation (Figure 17) occurring along synclinal axes (Figure 11). It was also found that the Potchefstroom Anticline was not active during Malmani Dolomite times.

After a prolonged period of relative tectonic stability during the development of the Malmani Dolomite, a rejuvenation of a number of dormant structural elements occurred at the end of the cycle of deposition of this formation. The Hartbeesfontein Anticline and Johannesburg Dome became particularly active at this stage, resulting in maximum subaerial erosion on and adjacent to these structures. That the latter was the most active portion of the Hartbeesfontein Anticline is illustrated in Figure 16, in which an apparent thickening south-westwards away from the Johannesburg Dome is shown, being due to a decrease in subaerial exposure and weathering of the formation in this direction. Thus, despite an original increase in thickness of the Malmani Dolomite to the north-west, the formation now displays an apparent thickening inwards towards the centre of the synclinorium (Figure 17). The dangers of using total thicknesses of any formation in the construction of isopach maps, to be used in paleogeographic reconstructions, have been revealed. Secondary fold trends were also found to have been active during post-Malmani Dolomite times, maximum brecciated chert thicknesses (Figure 24) being developed along structural highs. Although it has not, due to abundant strike-faulting, been possible to determine true or apparent thicknesses of the Malmani Dolomite around the Vredefort Dome, no evidence exists to suggest that this structure was positively active in post-Malmani Dolomite times. In the event of major updoming at this time, the Malmani Dolomite, already thin in that area, would have been completely removed, save for a thick residual chert accumulation.

During the deposition of the Timeball Hill Formation in the Potchefstroom Synclinorium, the Johannesburg Dome for the first time, and the Potchefstroom Anticline, again, exerted a control on the sedimentary pattern. As shown in Figure 28, the Lower Timeball Hill Formation thickens to the south, off the Johannesburg Dome, thereby implying that the above structure acted as a positive tectonic feature during these times. It is not possible to accurately define the activity of the Hartbeesfontein Anticline during Timeball Hill times. However, as the activity of this structure appears to be closely related to that of the Johannesburg Dome, it seems reasonable to suggest that the Hartbeesfontein Anticline was showing signs of activity, at least during the deposition of the Timeball Hill Formation in the Potchefstroom Synclinorium.

The north-south cross-section showing the variation in thickness of Lower Timeball Hill Formation (Figure 32), when extended southwards across the Vredefort Dome, indicates that this structure was negative during the deposition of the unit in question. The basement high further to the south is considered to have maintained its positive attitude (Table 5 and Figure 32), thus ruling out the suggestion made before, that the Timeball Hill Formation may have been deposited in an open-sea.

Although no concrete evidence exists for this conclusion, the general cratonic setting of the Transvaal Basin argues against an open-sea depository, the latter being more typical of marginal seas.

Following on the deposition of the Upper Timeball Hill Formation, major uplift occurred along the Hartbeesfontein Anticline, particularly to the north-west and north-east of the present synclinorium. Erosion of the Timeball Hill Formation resulted, such that the upper unit of this formation is most poorly developed adjacent to the above structure (Figure 29). The upper Timeball Hill Formation also thins to the north in this figure, considered to be due to uplift, although less intense than to the east and west, along the Hartbeesfontein Anticline to the north of Carletonville. Thus, an unconformity has been developed at the top of the Timeball Hill Formation. While major uplift along the northern limb of the synclinorium took place in post-Timeball Hill times, it is unlikely that such movement of the Vredefort Dome occurred. In the event of major updoming of the latter at the above time, the Timeball Hill Formation should, as a result of erosion, display a marked thinning onto the dome. However, as illustrated in Figure 28, the formation attains its maximum development in this area.

It has been mentioned previously (p. 9) that the basal representative of the Ongeluk Formation is either volcanic, quartzitic, or tillitic. While it has not been possible to observe the latter relationship in the field, it is felt that this rock-type, where present, belongs to the Ongeluk Formation. Button (1968) suggested that this tillitic horizon or tilloid could have been formed either by glacial or turbidity action. Having mapped its variation in thickness, the above author favoured the latter origin, concluding that turbidity flows would be expected to commence in tectonically positive areas. The distribution of the tilloid in the Potchefstroom Synclinorium is in agreement with these ideas, being well-developed to the south of Westonaria, which is the closest occurrence of the Ongeluk Formation to the Johannesburg Dome in this direction. It is considered that a turbidity current, originating in post-Timeball Hill times on the tectonically positive Johannesburg Dome, was responsible for the tilloid. Further to the west, the tilloid is not developed, while its distribution directly south of the above dome is unknown, due to a lack of borehole control.

As shown in Table 5, the major structural elements defining the Potchefstroom Synclinorium, particularly those to the north, north-west and south of the structure, namely the Hartbeesfontein Anticline including the Johannesburg Dome and the Vredefort Dome, are considered to have been most active in late- or post-Transvaal times. The outstanding feature shown in this table is that, while during and after the deposition of the Timeball Hill Formation the Vredefort Dome was completely inactive, this structure, in late- or post-Transvaal times, *became a major* positive tectonic feature. This phenomenon, it is felt, can only be explained if the Vredefort Dome is considered as an independent structural entity, as proposed by Brock and Pretorius (1964a), the movement of which was largely unrelated to other tectonics within the basement. The above conclusions, regarding the age of the Vredefort Dome, are in agreement with the paleomagnetic and radiometric findings of Hargraves (1970) which indicated that the Vredefort Dome is late- or post-Transvaal in age, having formed between 1970 and 2040 million years. The overfolded disposition of all strata within the Potchefstroom

Synclinorium, up to the Daspoort Quartzite, also testifies to a late- or post-Transvaal updoming of this structure.

As discussed in an earlier chapter (p. 15) and shown in Figure 5, the longitudinal fold trend has been more dominant than the transverse, all domical and basinal structures, within the synclinorium, being elongated parallel to the former. It is felt, however, that this elongation is due to flattening of initially symmetrical domes and basins, through the reactivation of the longitudinal trend during the final evolution of the Potchefstroom Synclinorium, in late- or post-Transvaal times. Through the compilation of results from previous chapters, which are summarized in Table 5, it has been shown that the Potchefstroom Synclinorium was not, in Malmani Dolomite times, a "structural entity in its own right" as proposed by Brock (1961) and was, even during later geologic periods, closely related to the Main Transvaal Basin, in that introduction of clastic material took place from the north, during Timeball Hill times.

THE BASIN ANALYSIS - A SUMMARY

The most interesting aspects of Table 6 are the different styles of sedimentation in each of the units considered and the effects of basement tectonics on the development of these units. Deposition of the Malmani Dolomite took place under shallow and warm-saline conditions, during times at which the Potchefstroom Synclinorium was part of the Main Transvaal Basin. A low-energy environment prevailed, controlled by the extreme stability of the craton during these times. Three depositional environments, which developed during alternating transgressive and regressive cycles, have been delineated in the Malmani Dolomite. These are the supratidal, intertidal and subtidal environments, being characterized by carbonaceous shales and massive to finely-laminated dolomites, domical stromatolites, oncolites and oolites, and columnar stromatolites, respectively. The supratidal environment is considered to be of particular importance in the genesis of highly saline, magnesium-rich waters, containing large amounts of silica, which were responsible for dolomitization and chertification of previously formed limestone.

At the end of Malmani Dolomite times a major period of uplift took place along the Hartbeesfontein Anticline, leading to subaerial erosion of the dolomite and residual concentration of chert. A brecciated chert zone was thereby formed at the base of the Fountains Formation, with maximum thicknesses along structural highs. The increased tectonic activity signalled the beginning of shallow to deep-water clastic, as opposed to wholly shallow-water chemical, sedimentation, resulting from greater differential uplift and subsidence in the source area and depository, respectively. During Timeball Hill times, the Potchefstroom Synclinorium was becoming separated from the main Transvaal Basin by the Hartbeesfontein Anticline, with the development of this formation taking place in each structural nit at different times. Within the Potchefstroom Synclinorium, a major delta, emanating from the north, has been recognized. Massive quartzites in association with carbonaceous and finely-laminated shales developed in the proximal facies of the delta, while in more distal environments only finely laminated shales in association with lenticular quartzites were deposited. The latter association was also recognized north of the Hartbeesfontein Anticline, indicating that the Timeball Hill Formation, in the Transvaal, developed during at least two periods of sedimentation, being related to a southwards regressing shore-line. It is considered that during Upper Fountains Formation and Timeball Hill times, a cratonic source, as opposed to an external source terrain (Sloss, 1962), still prevailed, as demonstrated by the high degree of maturity of the quartzites in each formation.

* *

TABLE 6

THE BASIN ANALYSIS

UNIT	BASIN GEOM.	LITHIC FILL	ARRANGEMENT	TECTONIC SETTING
MALMANI DOLOMITE FORMATION	Wide s ; shallow depository. Paleoslope to north-west off a basement high to the south. Axis of depository to the north of the Potchefstroom Synclinorium. Secondary longitudinal and transverse structural trends influenced deposition.	Chemical sediments predominate. Reworked autochthonous and minor allochthonous sediments occur. Dolomite and chert constitute greater than 95% of the formation. Carbonaceous shales occur throughout. Quartzites only at base.	Total formation thickens down the paleoslope to the north-north-west. Diachronous zones developed initially during southwards transgression of the shoreline, which during later times regressed northwards and was followed by a second period of transgression up the paleoslope.	Stable intracratonic. Period of mild subsidence maintaining a shallow depositional environment throughout Malmani Dolomite times. Limited or no uplift around the depository.
LOWER PRETORIA GROUP 1. Fountains Formation	First stage in the evolution of the Potchefstroom Synclinorium. Regional paleoslope still to the north	Brecciated chert, boulder conglomerates, chert-rich quartzites, and siliceous shales.	Brecciated chert is thickest over structural highs. Clastics derived from immediate and distal source, an occur as channel-fi ngs.	Moderate but differential uplift within the depository followed by mild to moderate uplift in source area and subsidence in basin, which was responsible for the high-energy fluvial action.
2. Timeball H. l Formation	Basin opens to the north over an anticlinal ridge, deepening to th south. A topographic high existed in the north-east while a similar, but laterally more persistent structure probably *existed south of the area* being investigated.	Clastic sediments predominate. Protoquartzitic sands constitute from 0-33% of the total fill. Other clastics are laminated ferruginous and carbonaceous shales. Minor chemical sediments *in the form of dolomite* and chert occur at the base	Lower unit of the formation thickens to the south, south-west and south-east followed by a marked thinn-ng to the south-west. Unit also thins towards the topographic high in the north-east. Laminated-ferruginous *and carbonaceous shales in* the central northern area grade southwards into the former alone. Thick-massive quartzites in the north become lensoid in the south, being absent in the south-west. Upper unit thickens from north-east and north-west towards centre of synclinorium.	Intracratonic basin with mild to moderate subsidence. Uplift in distal source area.

APPENDIX I : Trend Surface Analysis

Trend surface analysis involves the separation of the local or small-scale components from the regional trend which, according to Merriam (1965) has the effect of amplifying the former, thereby making it more conspicuous.

Ordinary two-dimensional graphs, in which values of a dependent variable, y, are plotted against an independent variable, x, are intended to reveal any systematic relationship between y and x. If the points plotted fall approximately on a straight line, a line of best-fit or regression line, of the form $y = a + bx$, can be calculated. If, however, the points do not lie on a straight, but rather a curved line, the line of best-fit will then be of a higher polynomial form of the quadratic, cubic, quartic, or even more involved types.

Areally distributed data are frequently encountered in geological investigations, in which a dependent variable z varies with two independent variables x and y. In a similar manner to that discussed above, polynomial surfaces, instead of lines, of the form $z = a + bx + cy$ can be calculated, having the best-fit to the variable parameter (z). In practice, polynomial surfaces from the 1st to 6th degree are generally fitted to the data. A computer programme, written by O'Leary, Lippert and Spitz (1966) for an I.B.M. 7040 Computer, designed for 500 data points, was used in the present investigation. This programme was modified by P.A. Esselaar of the Economic Geology Research Unit for use with an I.B.M. 360 Computer for 750 data points.

Onc a best-fit equation for each of the six surfaces has been determined, a value, ze, at each data point corresponding to the calculated value of the surface at that point, is obtained. The actual value at the data point (z) will seldom lie on the surface, giving a positive difference where the measured value of the variable is greater than, and a negative value when less than, the trend surface value at each point. These differences are referred to as residuals and represent local variations in the data-set. The polynomial surfaces are determined in such a way that the sum of the squares of the residuals ($s = \Sigma(z - ze)^2$) is at a minimum, referred to as the method of least squares.

It is necessary to be able to test the degree of significance of individual polynomial surfaces. There are a number of measures of this parameter, also termed the "goodness of fit" or "strength" of the surface, two of which are considered to be most useful. The percentages of total variation explained by the surface, as well as the coefficient of correlation, were calculated in the computer programme used, both being reliable measures of significance. The total variation in the mapped variable has been defined by O'Leary, Lippert and Spitz (1966) as $v = \Sigma (z - \bar{z})^2$, where z is the actual value at each data point and $\bar{z}$ is the mean z value. The variation not explained by the surface is the sum of the squared residuals (s), as defined above, with that explained by the surface thus given by $E = v - s$. The percentage of the total variation explained by the surface is then given by : $^E/_v \times 100$. The coefficient of correlation (c) can be directly calculated : $c = (^E/_v)^{\frac{1}{2}}$, serving a similar function to that determined by two-dimensional regression lines.

It is also necessary to compare the relative significance of each of the six calculated surfaces. Allen and Krumbein (1962) proposed that the increase in percentage "fit" explained by each succeeding surface is an ideal means of comparison. If, for example, the linear surface explained 51% of the total variation, the quadratic 59%, the cubic 59.8% and the quartic 60.5%, the above authors would conclude that" most of the primary-trend information has been squeezed out of the map by the time the quadratic surface was fitted".

APPENDIX II : MALMANI DOLOMITE

MACROSCOPIC PARAMETERS (PERCENTAGES)

BOREHOLES UD 11, UD12, UD 15 - Oberholzer District/and
BOREHOLE K4 - Westonaria District

DEPTH (METRES)	CARB. SHALE	MASSIVE DOLOM.	COL. STROMAT.	DOMIC. STROMAT.	OOLITES	CHERT
0 - 16.8	1.0	-	-	0.5	1.0	6.7
16.8 - 33.6	-	-	-	0.5	-	7.0
33.6 50.4	-	-	-	-	-	3.7
50.4 - 67.2	-	-	6.7	-	-	3.8
67.2 - 84.0	-	-	-	-	0.3	3.1
84.0 - 100.8	-	-	-	-	-	3.7
100.8 - 117.6	-	-	-	0.8	0.3	4.5
117.6 - 134.4	-	-	-	1.5	-	6.6
134.4 - 151.2	-	-	-	0.5	-	2.5
151.2 - 168.0	-	-	1.5	1.2	-	1.2
168.0 - 184.8	0.5	-	-	2.1	-	3.2
184.8 - 201.6	1.2	-	-	2.7	-	3.8
201.6 - 218.4	-	-	-	2.4	-	2.5
218.4 - 235.2	-	-	-	7.4	-	4.5
235.2 - 252.0	-	-	-	3.9	-	2.7
252.0 - 268.8	-	-	-	3.7	-	0.5
268.8 - 285.6	-	-	-	4.5	-	0.6
285.6 - 302.4	-	-	-	1.5	-	0.2
302.4 - 319.2	-	-	-	2.4	-	1.1
319.2 - 336.0	-	-	-	1.2	-	3.8
336.0 - 352.8	-	-	-	0.9	-	1.2
352.8 - 369.6	-	-	-	0.5	-	0.9
369.6 - 386.4	-	17.0	-	-	-	-
386.4 - 403.2	-	24.0	-	-	-	-
403.2 - 420.0	-	63.0	-	-	-	-
420.0 - 436.8	0.3	24.0	-	-	-	-
436.8 - 453.6	0.5	11.0	-	-	-	-
453.6 - 470.4	1.7	16.0	-	1.4	-	0.5
470.4 - 487.2	-	13.0	-	0.6	-	1.1
487.2 - 504.0	0.8	2.0	-	1.9	-	1.0
504.0 - 520.8	1.3	-	-	4.2	0.3	2.4
520.8 - 537.6	0.3	-	-			

APPENDIX II (Continued)

DEPTH (METRES)	CARB. SHALE	MASSIVE DOLOM.	COL. STROMAT.	DOMIC STROMAT.	OOLITES	CHERT
537.6 - 554.4	0.4	-	-	2.2	-	2.2
554.4 - 571.2	0.2	-	-	2.6	-	2.7
571.2 - 588.0	0.6	-	-	1.3	-	3.2
588.0 - 604.8	0.8	-	1.8	0.9	-	6.3
604.8 - 621.6	0.2	-	3.0	2.7	-	5.0
621.6 - 638.4	0.1	-	9.5	2.1	-	6.2
638.4 - 655.2	1.0	-	-	2.4	-	5.8
655.2 - 672.0	0.5	-	-	1.2	-	5.1
672.0 - 688.8	1.7	-	-	1.3	-	5.5
688.8 - 705.6	0.4	-	-	0.9	-	8.6
705.6 - 722.4	3.7	-	-	2.4	0.3	3.7
722.4 - 739.2	-	-	-	0.4	-	1.0
739.2 - 756.0	3.0	-	7.4	3.2	0.1	5.5
756.0 - 772.8	0.3	-	9.3	1.6	-	2.4
772.8 - 789.6	0.1	-	6.6	1.8	-	0.3
x——x——x						
789.6 - 806.4	0.7	-	17.0	3.7	-	0.8
806.4 - 823.2	0.9	-	15.0	2.1	-	1.3
823.2 - 840.0	1.7	-	12.0	1.4	-	2.4
840.0 - 856.8	1.6	-	12.0	1.2	-	2.3
856.8 - 873.6	0.2	-	20.0	2.2	-	2.9
873.6 - 890.4	2.7	-	-	0.4	0.4	8.8
890.4 - 907.2	1.4	-	-	1.0	2.4	6.0
907.2 - 924.0	0.9	-	2.0	0.3	0.5	5.6
924.0 - 940.8	1.3	-	-	1.1	0.3	3.5
940.8 - 957.6	-	-	4.8	-	2.2	8.6
957.6 - 974.4	0.2	-	4.2	1.1	0.7	5.7
974.4 - 991.2	0.7	-	3.0	0.6	1.8	5.4
991.2 - 1008.0	6.2	-	-	2.0	2.7	5.4
1008.0 - 1024.8	2.0	-	2.4	2.8	2.0	5.0
1024.8 - 1041.6	0.1	-	3.0	0.6	0.6	2.8
1041.6 - 1058.4	2.0	-	4.8	-	2.3	2.3
1058.4 - 1075.2	1.2	7.8	-	-	0.3	0.3
1075.2 - 1092.0	0.7	14.2	-	-	-	0.1
1092.0 - 1108.8	1.2	3.4	-	0.7	-	-
1108.8 - 1125.6	0.3	1.0	2.6	2.2	-	1.0
1125.6 - 1142.4	1.0	3.6	-	1.3	-	0.6
1142.4 - 1159.2	0.6	11.0	-	-	-	-
1159.2 - 1176.0	0.5	15.0	-	-	-	-
1176.0 - 1192.8	17.0	7.8	-	-	-	-
1192.8 - 1210.0	37.0	4.8	-	-	-	-

xxx Zone of Variable Thickness (v)

Values refer to the percentages at each parameter in the total intervals shown above. Zero depth was taken as the top of the oncolite horizon.

0 - 386.4 metres - From log of Borehole K4

386.4 - 1210 metres - From Composite of logs of Boreholes UD 11, 12 and 15.

APPENDIX III : MALMANI DOLOMITE - GEOCHEMISTRY (PERCENTAGES)

BOREHOLE UD 15 - Oog van Elandsfontein 114, Oberholzer District

DEPTH (METRES)	SAMPLE NUMBER	Ca	Mg	Fe	Mn	Na
54 - 60	CV168	14.5	8.6	.0090	.0048	.0024
60 - 66	CV166	21.1	12.9	.0031	.0032	.0023
66 - 79	CV164	20.2	12.1	.0042	.0032	.0022
79 - 93	CV162	21.4	12.8	.0040	.0038	.0023
93 - 107	CV160	15.5	9.5	.0034	.0028	.0007
107 - 122	CV158	20.0	12.1	.0044	.0034	.0007
122 - 136	CV156	14.4	8.6	.0032	.0026	.0007
136 - 150	CV154	21.4	12.8	.0040	.0039	.0006
150 - 164	CV152	21.1	12.8	.0047	.0039	.0008
164 - 178	CV150	20.7	12.4	.0045	.0040	.0006
178 - 192	CV148	11.9	7.0	.0019	.0019	.0005
192 - 205	CV146	14.4	8.6	.0029	.0026	.0007
205 - 220	CV144	21.1	12.7	.0025	.0039	.0007
220 - 233	CV142	21.4	12.8	.0023	.0039	.0007
233 - 247	CV140	21.4	12.8	.0023	.0037	.0007
247 - 261	CV138	19.9	11.8	.0037	.0036	.0007
261 - 275	CV136	21.4	12.8	.0023	.0044	.0006
275 - 289	CV134	21.3	12.7	.0029	.0048	.0006
289 - 303	CV132	19.7	11.7	.0029	.0037	.0008
303 - 317	CV130	21.6	12.7	.0038	.0041	.0007
317 - 330	CV128	21.1	12.7	.0034	.0054	.0007
330 - 344	CV126	21.0	12.7	.0045	.0072	.0008
344 - 357	CV124	18.4	10.9	.0042	.0074	.0009
357 - 371	CV122	16.0	9.4	.0043	.0065	.0010
371 - 385	CV120	20.7	12.4	.0059	.0078	.0007
385 - 398	CV118	18.5	10.9	.0073	.0089	.0008
398 - 413	CV116	21.1	12.6	.0060	.0088	.0007
413 - 430	CV114	21.4	12.7	.0044	.0074	.0009
430 - 446	CV112	21.6	12.6	.0040	.0081	.0008
446 - 459	CV110	21.4	12.8	.0050	.0063	.0009
459 - 475	CV108	19.7	11.7	.0038	.0049	.0008
475 - 492	CV106	21.1	12.6	.0034	.0055	.0009
492 - 506	CV104	21.1	12.5	.0039	.0052	.0008
506 - 521	CV102	21.0	12.7	.0049	.0044	.0010
521 - 540	CV100	18.4	10.9	.0054	.0034	.0009
540 - 553	CV 98	21.1	12.7	.0026	.0043	.0009
553 - 566	CV 96	21.3	12.8	.0023	.0044	.0008
566 - 579	CV 94	18.4	11.0	.0023	.0032	.0008
579 - 594	CV 92	21.1	12.7	.0040	.0043	.0009
594 - 609	CV 90	21.6	12.5	.0025	.0032	.0007
609 - 624	CV 88	21.3	12.9	.0028	.0039	.0007
624 - 637	CV 86	17.3	10.3	.0023	.0039	.0007
637 - 650	CV 84	20.7	12.5	.0039	.0034	.0008
650 - 664	CV 82	19.0	11.4	.0050	.0028	.0008
664 - 677	CV 80	21.4	12.7	.0030	.0025	.0006
677 - 690	CV 78	21.4	12.9	.0016	.0020	.0007
690 - 703	CV 76	21.4	12.9	.0015	.0020	.0007
703 - 716	CV 74	17.3	10.3	.0034	.0025	.0008
716 - 729	CV 72	21.4	12.8	.0028	.0034	.0006
729 - 742	CV 70	21.1	12.7	.0030	.0032	.0008
742 - 755	CV 68	19.2	11.6	.0050	.0030	.0010

APPENLIX III (Contin

DEPTH (METRES)	SAMPLE NUMBER	Mg	Fe	Mn	Na
755 - 768	CV 66	12.9	.0035	.0030	.0007
768 - 781	CV 64	10.4	.0029	.0029	.0009
781 - 793	CV 62	12.8	.0052	.0037	.0008
793 - 807	CV 60	12.8	.0039	.0036	.0007
807 - 822	CV 58	11.6	.0029	.0025	.0007
822 - 835	CV 56	12.8	.0028	.0034	.0007
835 - 849	CV 54	12.9	.0024	.0036	.0005
849 - 862	CV 52	12.6	.0022	.0043	.0006
862 - 877	CV 50	12.6	.0029	.0032	.0007
877 - 890	CV 48	11.5	.0028	.0032	.0006
890 - 904	CV 46	12.7	.0035	.0037	.0007
904 - 918	CV 44	12.9	.0037	.0036	.0007
918 - 931	CV 42	11.9	.0036	.0032	.0006
931 - 946	CV 40	12.9	.0014	.0026	.0007
946 - 959	CV 38	13.0	.0017	.0025	.0008
959 - 972	CV 36	11.6	.0012	.0024	.0008
972 - 985	CV 34	11.4	.0025	.0027	.0007
985 - 998	CV 32	12.8	.0023	.0026	.0012
998 - 1012	CV 30	12.8	.0024	.0027	.0006
1012 - 1025	CV 28	12.5	.0017	.0023	.0007
1025 - 1038	CV 26	12.9	.0027	.0028	.0008
1038 - 1052	CV 24	12.9	.0043	.0035	.0009
1052 - 1066	CV 22	12.6	.0060	.0042	.0011
1066 - 1079	CV 20	11.8	.0049	.0037	.0007
1079 - 1095	CV 18	11 9	.0064	.0054	.0013
1095 - 1105	CV 16	11.9	.0079	.0090	.0008
1105 - 1120	CV 14	12.3	.0081	.0122	.0009
1120 - 1133	CV 12	12.2	.0143	.0194	.0008
1133 - 1147	CV 10	12.7	.0035	.0068	.0026
1147 - 1160	CV 8	11.6	.0043	.0058	.0028
1160 - 1172	CV 6	12.4	.0090	.0089	.0027
1172 - 1186	CV 4	11.3	.0255	.0168	.0026
1186 - 1198	CV 2	10.1	.0415	.0192	.0026
1198 - 1210	CV 1	6.2	.0430	.0149	.0026

Two samples were taken [illegible]rval shown above. One composite per interval was prepared for chem[illegible]is. The oncolite horizon was not present in B.H. UD 15, having been re[illegible] erosion during the formation of the brecciated chert zone. Sampli[illegible] started at 54 metres below the stratigraphic position of the oncol[illegible]n.

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PLATE I

A. Intraformational Conglomerate

B. Finely-Laminated Dark Dolomite

C. Variegated or Partly Recrystallized Dolomite

D. Recrystallized Dolomite

E. Veined Dolomite

PLATE II

Large Domical Stromatolite with
Small Parasitic Domes

PLATE III

Algal-Laminated Sediments

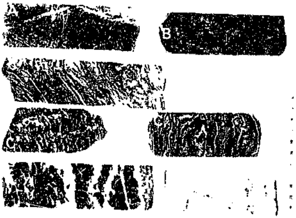


PLATE IVa

		Structural Formulae
A.	Cryptozoon Stromatolite	SH-C
B.	Cryptozoon Stromatolite	SH-C LLH-S SH-C
C.	Oncolites	

PLATE IVb

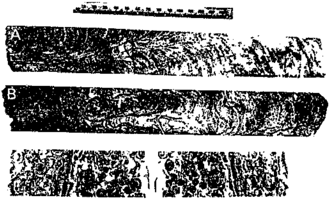
Plan View of Small Cryptozoon

Stromatolites

PLATE IVc

Plan View of Large Cry[illegible]

Stromatolites


A
B

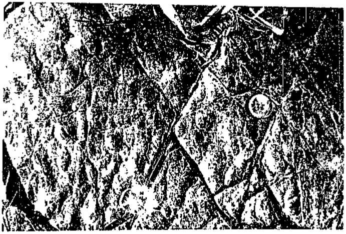


PLATE V

A. Graded Chert Oolites in Chert

B. Dolomite with Occasional Chert Oolites in Dolomite

C. Chert Oolites in Dolomite

PLATE VIa

Ripple Marks in Chert

PLATE VIb

Interference Rip[illegible] in Chert

PLATE V

A. Graded Chert Oolites in Chert

B. Dolomite with Occasional Chert Oolites in Dolomite

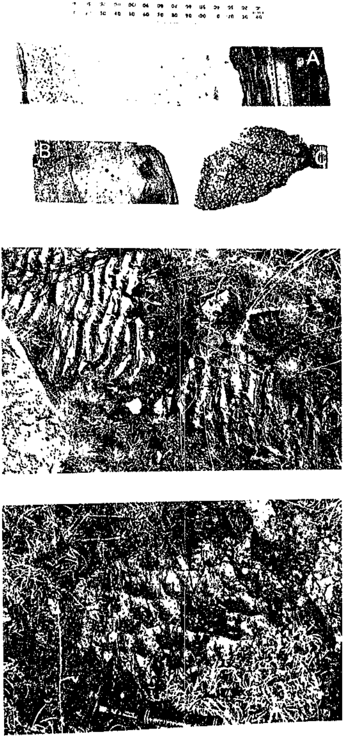
C. Chert Oolites in Dolomite

PLATE VIa

Ripple Marks in Chert

PLATE VIb

Interference Ripple Marks in Chert



A
B

PLATE VII

Brecciated Chert Zone at

Loch Vaal

PLATE VIII

Brecciated Chert Zone - Fresh

Samples from Borehole Cores

Note : A. Oolite Fragments

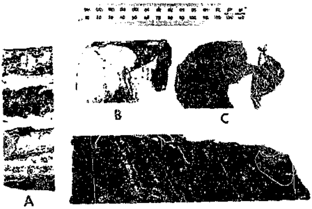
B. *Chert Fragment* with a Domical Stromatolite

C. Light Coloured Quartzite Fragments

PLATE IX

Chert Boulder Conglomerate - Pologround

Member



natolite

PLATE X

Ripple Marked Carbonaceous Shale with
Cross-bedded Silt Infilling

Timeball Hill Formation

PLATE XI

Massive Gatsrand Quartzites
South of Carletonville

Timeball Hill Formation

PLATE XII

Lenticular Gatsrand Quartzites
West of Vanderbijlpark

Timeball Hill Formation